DEMec - Dep. of Mechanical Engineering
SAIC- Automation, Instrumentation and Control Section
Master in Mechanical Engineering

Electromechanical Systems

1st Year– 2nd Semester
2025-2026

Support documents to TP classes

Mechanical Systems and Feedback Devices used with Electric Motors

Paulo Abreu

2026 Edition

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Mechanical Systems and Feedback Devices
used with Electric Motors

Paulo Abreu
pabreu@fe.up.pt
2026

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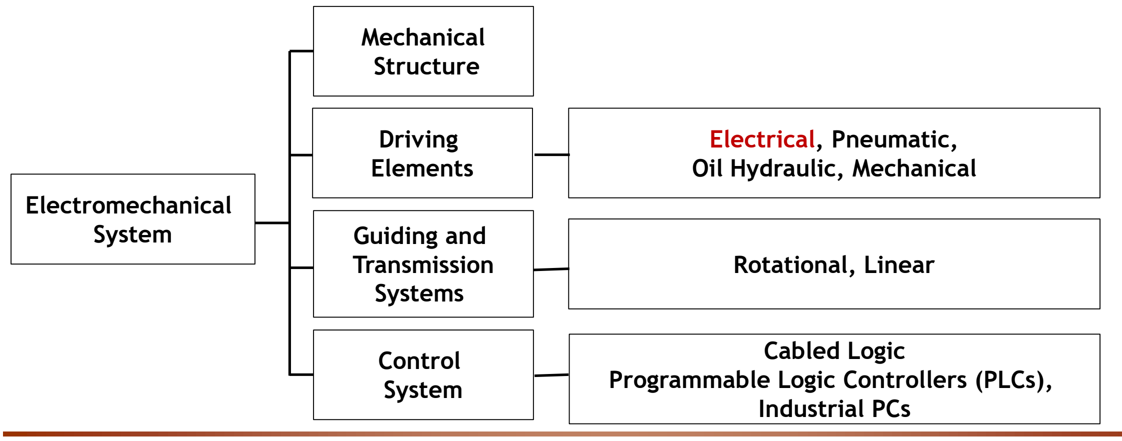
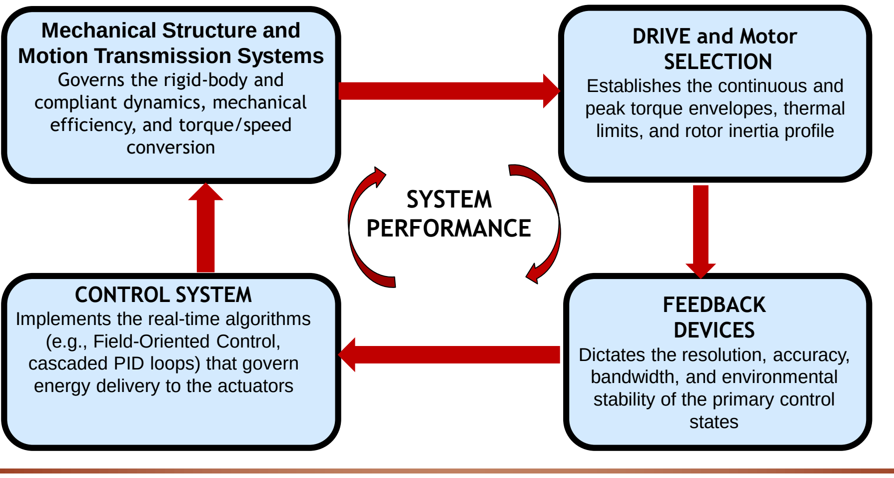
Electromechanical Architecture Overview



Subsystems Interdependency Analysis



Subsystems Interdependency Analysis

- The overall performance of an electromechanical system is influenced by far more than just the choice of the drive component, such as an electric motor. While selecting a high-efficiency motor is important, it must be matched with an equally capable mechanical structure, motion transmission system, and control strategy. Each of these subsystems plays a critical role in determining the efficiency, precision, reliability, and responsiveness of the machine
- Integrating a high-efficiency electric motor with a poorly selected or low-performance gearbox can significantly degrade the system's overall efficiency. Mismatched gear ratios, excessive backlash, or low gearbox transmission efficiency can lead to energy losses, vibration, noise, and reduced component lifespan. Therefore, mechanical motional transmission systems must be chosen not only for their compatibility with the motor but also for their ability to handle the required loads, speeds, and duty cycles
- Equally important is selecting appropriate feedback devices, such as encoders, resolvers, or LVDTs, that provide essential information on position, speed, and other variables. These devices must be compatible with both the motor control system (e.g., servo drives or variable frequency drives) and the specific application requirements
- Environmental factors such as temperature, vibration, and electromagnetic interference should also be considered in the selection process to ensure reliable operation over time

Achieving optimal system performance requires a holistic approach, where the mechanical, electrical, and control components are designed and selected to function cohesively as a fully integrated system

Subsystems Analysis
Motion Transmission Systems

Mechanical Guiding Systems

- **Function**: mechanical guiding systems are designed to direct and control the movement of mechanical components along a specific path. They ensure that parts move smoothly and accurately in the desired direction
- **Components**: these systems typically include linear guides (such as ball rail, roller rail, and cam roller systems) and rotary guides. They may also involve elements that reduce friction, such as bearings and bushings

Mechanical Transmission Systems

- **Function**: mechanical transmission systems transfer power and motion from one part of a machine to another. They adjust the speed, torque, and direction of the mechanical power to suit the requirements of the application
- **Components**: these systems include various types of gearboxes (spur, planetary, helical, bevel, worm, harmonic drive), screw drives (ACME, planetary roller, ball screw), and motion conversion systems (rack and pinion, toothed belt and sprocket)

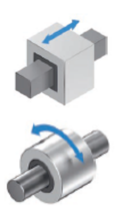
Mechanical Guiding Systems
Linear and Rotary Guides

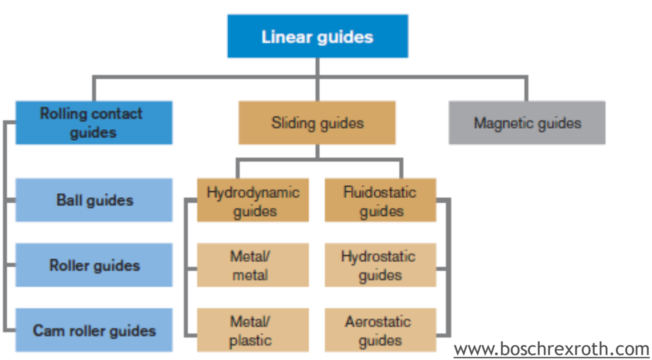
In electromechanical systems that use electric motors to drive motion, the system's effectiveness depends heavily on how motion is supported and directed. This is where **guiding elements,** specifically **linear guides** and **rotary guides,** come into play

- **Linear Guides** are mechanical components that constrain and guide motion along a straight path with minimal friction and high rigidity. They are essential for applications that require precise linear displacement, such as CNC machines, pick-and-place robots, and linear actuators
- **Rotary Guides** support rotational motion and are commonly used in systems with rotating shafts, wheels, or arms. These include **bearings, bushings, and rotary tables**
- **Key aspects to consider**
  - **Precision:** High-accuracy linear guides enable repeatable, accurate positioning
  - **Load Handling:** They support heavy loads while maintaining alignment and reducing deflection
  - **Smooth Motion:** Rolling contact elements minimize friction, improving energy efficiency and responsiveness
  - **Stability:** Ensure smooth, controlled rotation to reduce vibrations and mechanical wear
  - **Efficiency:** Low-friction bearings improve motor performance by reducing energy loss
  - **Durability:** Critical in high-speed or high-load environments to maintain system reliability.

Mechanical Guiding Systems
Linear and Rotary Guides

- Linear guides
- Rotary guides





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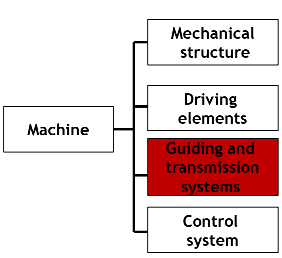
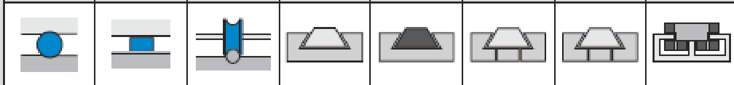


The selection of the guiding mechanism establishes the system's baseline friction profile. In electromechanical systems, minimizing kinetic and static friction variance is essential to eliminate stick-slip phenomena, which degrade position tracking at low velocities

Mechanical Guiding Systems
Linear Guide Taxonomies and Performance Profiling

Characteristics	Rolling contact guides			Hydrodynamic sliding guides		Fluidostatic sliding guides		Magnetic guide
	Ball guide	Roller guide	Cam roller guide	Metal/ metal	Metal/ plastic	Hydrostatic guide	Aerostatic guide	Magnetic suspension
								
Load-bearing capability	+++	+++	++	+++	+++	+++	o	+++
Rigidity	++	+++	+	+++	++	+++	o	+
Accuracy	++	++	++	+	+	++	++	+++
Friction characteristics	++	++	++	+	+	+++	+++	+++
Speed	+++	+++	+++	+	+	+++	+++	+++
Damping characteristics	+	+	+	+++	+++	+++	+++	+++
Operating safety	+++	+++	+++	+++	+++	+	+	+
Standardization	+++	+++	+++	+	+	o	o	o
Service life	++	++	++	++	++	+++	+++	+++
Costs	++	++	++	+++	+++	+	+	o

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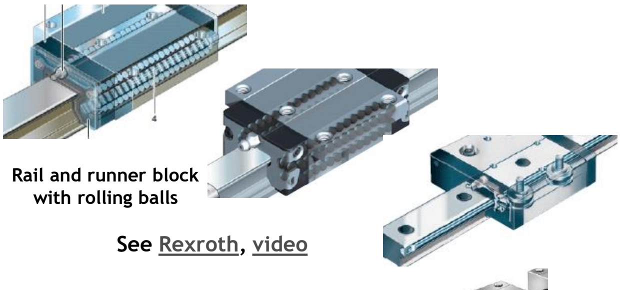
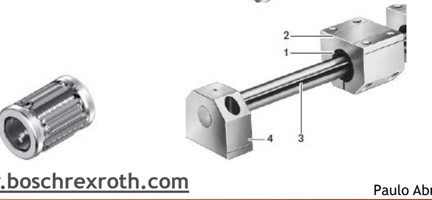
Mechanical Guiding Systems
Linear Guides

- **Linear guides** (with rolling contact)
  - **ball rail systems**: feature point-contact interfaces providing minimal rolling friction, making them ideal for high-speed, lower-mass positioning platforms
  - **roller rail systems**: employ line-contact geometry, which significantly boosts stiffness and load capacity at the expense of slightly elevated rolling resistance
  - **cam roller systems**: use supported track rollers; they handle high linear velocities and misalignment well, though with reduced overall stiffness
- **Linear bushings and shaft** (with rolling contact)
- **Sliding Guides (Hydrodynamic, Hydrostatic, Aerostatic):** Eliminate rolling elements entirely. Hydrostatic and aerostatic guides introduce fluid or gas films, delivering nearly zero static friction and outstanding damping properties



Rail and runner block with rolling balls

See Rexroth, video



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Mathematical Modeling of Rolling Friction and Sealing Overhead

The total resistive friction force F_R experienced by a linear profiled rail system under an applied normal load F_N is modeled by the following mathematical expression:

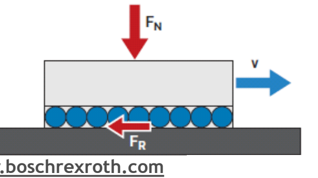
$F_R = \mu \cdot F_N + F_{Seal}$ where

- μ is the empirical rolling friction coefficient inherent to the geometric configuration (typically ranging from 0.001 to 0.005 for ball and roller rail systems)
- F_N is the total normal force vector, including structural preloads
- F_{Seal} is the constant parasitic friction force introduced by the elastomeric wiper seals.

Note that in light-load or high-acceleration applications, F_{Seal} can contribute over 50% of the total mechanical resistance. This seal overhead generates a parasitic drag torque that must be factored into the continuous thermal sizing of the driving motor

Friction coefficients without seals (rolling friction)

Linear component	Friction coefficient μ without seal	Comment
Linear bushing and shaft	0.001 ... 0.004	Standard linear bushing
Ball rail system	0.002 0.003	2-point contact 4-point contact
Roller rail system	0.0004	Line contact
Ball screw assembly	0.004 0.010	2-point contact 4-point contact



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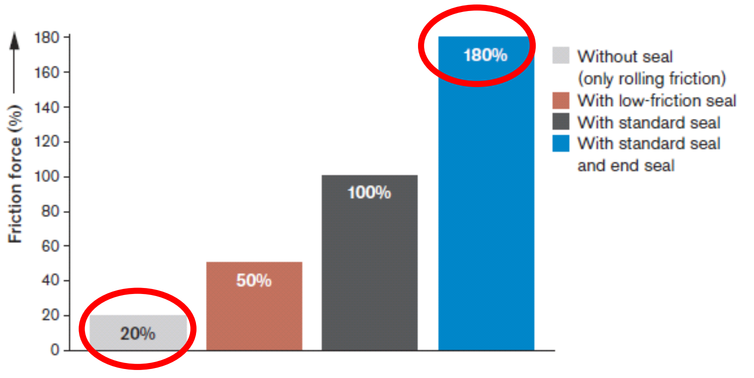
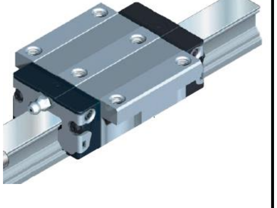
Linear Guides: Rolling Friction and Seals Friction

Effect of seals on friction forces on ball rail system, using a rail guide, with a preload of 2%





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Mechanical Guiding Systems
Rotary Guides

Rotary guides constrain motion to a rotational path, typically around a fixed axis. They reduce friction and support radial and axial loads, enabling efficient and controlled rotation. This function is essential in systems where parts rotate continuously or oscillate back and forth

Common Types of Rotary Guides

- **Ball Bearings:** use rolling balls between inner and outer races to reduce friction
- **Roller Bearings:** similar to ball bearings, cylindrical rollers are used for heavier load capacity
- **Bushings (Sleeve Bearings):** use sliding contact instead of rolling elements
- **Rotary Tables:** precision platforms that rotate workpieces or tools
- **Swivel Joints / Rotary Unions:** allow rotation while transferring fluids or gases




INA bearings   ISK bearings

DSTI swivel

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Mechanical Guiding Systems
Linear Guides and Performance Profiling

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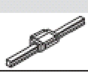
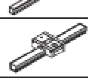
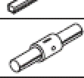
Guideway	Load capacity	Preload possibilities	Rigidity	Linear speed	Travel accuracy	Noise char-acteristics
Ball rail system 	+++	+++	+++	++	+++	++
Cam roller guide 	+	++	+	+++	++	+++
Linear bushing and shaft 	++	++	++ 1) + 2)	++	++	++

1) Open type
2) Closed type

+++ Very good   ++ Good   + Satisfactory

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Mechanical Guiding Systems
System Integration and Selection Criteria

The choice of **linear** and **rotary guides** to be integrated with electric motors into a machine requires balancing conflicting mechanical and dynamic criteria

$$Selection\ Criteria = f\,(Kinematics, Dynamics, Environment, Precision, Velocity, Environment)$$

- **Kinematics:** Match the path requirements (linear vector precision versus angular axis runout)
- **Dynamic Loading:** Evaluate peak acceleration forces, structural moment loads, and variable duty cycles
- **Precision and Velocity:** Balance positional repeatability with maximum operational linear/angular speeds
- **Environmental Resilience:** Account for particulates, aggressive chemicals, temperature extremes, and structural contamination

Using **inappropriate or low-quality guiding elements** can result in misalignment, excess friction, premature wear, or even failure of the mechanical system, regardless of how advanced the motor or control system is

Mechanical Transmission Systems in Electromechanical Applications

- Mechanical Transmission Systems are critical components in electromechanical systems, responsible for adapting the output of electric motors to the mechanical load's requirements. These systems, comprising gearboxes, screw drives, belts, pulleys, and couplings, modify parameters such as torque, speed, direction, and motion type (rotary to linear or vice versa) to ensure efficient and effective power transfer
- The selection of a suitable transmission system directly impacts the system's precision, energy efficiency, dynamic response, and mechanical robustness. For example, high-ratio planetary gearboxes offer compact solutions with high torque density, while ball screw drives provide smooth, accurate linear motion for positioning applications
- Integration with electric motors must consider factors like reduction ratio, backlash, moment of inertia, efficiency, and alignment. A mismatch between the motor and transmission system, such as pairing a high-efficiency motor with a poorly designed gearbox, can significantly reduce overall performance and energy utilization

Mechanical transmission systems are not just passive elements: a poorly engineered transmission network will degrade the overall performance of an otherwise optimal motor-drive package

Mechanical Transmission Systems

- Mechanical Transmission refers to the method of transferring **mechanical power and motion** from one part of a machine to another, usually from a **power source** (like an electric motor) to a **load** (such as wheels, tools, or actuators). It **controls** how motion is delivered, its **speed**, **direction**, **torque**, and **type of motion** (rotational or linear)

Common Types of Mechanical Transmission Systems:

- **Ball Screws and Lead Screws:** convert rotary motion into linear motion.
  Examples: ACME screw, Planetary roller, ball screw drive
- **Tooth Belts and Rack and Pinion:** convert rotary motion into linear motion
- **Belts and Pulleys:** transmit motion between shafts that are not in direct contact
- **Gearboxes:** transfer motion and torque between shafts. Used to increase torque or change speed/direction.
  Examples: spur gears, planetary, helical, bevel gears, worm gears, harmonic drives
- **Brakes and Clutches:** control when motion is stopped or engaged
- **Couplings and Shafts:** shafts transmit torque, while couplings connect shafts together

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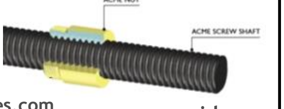
Mechanical Transmission Systems
Ball Screws and Lead Screws

- **Ball screw drive: rolling contact with spheres**
  - Utilize recirculating spherical balls to replace sliding with rolling friction. They achieve outstanding efficiency (η > 90%), exceptional axial rigidity, and highly predictable lifespans

www.hiwin.us

video

- **ACME screw drive: sliding contact between the threads**
  - Depend on direct sliding contact between threads, yielding low material costs and high dampening properties. However, they suffer from poor mechanical efficiency (η = 20\% - 60\%$) and rapid wear rates



www.nookindustries.com

video

- **Planetary roller screw drive: barreled surfaces of all the engaged rollers**
  - Employ threaded rollers revolving around the screw shaft. This configuration maximizes the surface contact area, providing extreme load capacities and high linear accelerations within a compact footprint

www.ewellix.com

video

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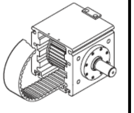
Mechanical Transmission Systems
Advanced Motion Conversion: Toothed Belts and Rack & Pinion Systems

Systems for converting rotational motion into linear motion

- **Toothed belt and sprocket**
  - Utilize a flexible, fiber-reinforced elastomer belt engaged with a synchronous multi-grooved pulley. They provide high linear speeds, quiet operation, and cost-effective travel over extended distances. However, compliance in the belt introduces a spring-damper effect, lowering the mechanism's structural resonant frequency
- **Rack and pinion: helical or straight tooth**
  - Consists of a circular gear (the pinion) engaging a linear gear track (the rack). Helical tooth geometries are preferred over spur profiles to optimize the contact ratio, minimize acoustic emissions, and reduce force ripple. They offer near-infinite stroke options and high force rigidity, but require precise mechanical alignment and ongoing lubrication strategies

www.phdinc.com

video


www.atlantadrives.com
www.stoeber.de
video

www.apexdynauk.com

Mechanical Transmission Systems
Comparison and Performance Profiling

Drive unit	Requirements				
	Thrust	Rigidity	Speed	Precision 1)	Noise characteristics
Ball screw	+++	+++	+	+++	++
Toothed belt	++	+	+++	+	++
Rack and pinion	+++	+++	++	++	++
Linear motor	++	+++	+++	+++	+++

1) Depending on the measuring system used, its accuracy, and the control system

+++ Very good
++ Good
+ Satisfactory

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Mechanical Transmission Systems
Belts - Pulley Systems

A **belt-pulley system** transmits power and motion between rotating shafts using a **flexible belt** looped over **two or more pulleys.** When one pulley is powered (usually by a motor), it drives the belt, which in turn rotates the other pulley(s). The operational characteristics are dictated by the profile geometry

video

- **Belt-Pulley systems are used for**
  - **Distance bridging** between shafts; **Speed variation**
  - **Shock absorption; Quiet operation**
- **Types of Belts**
  - **Flat Belts:** used for high-speed, low-torque applications; simple and low-cost
    - Rely entirely on friction contact against smooth pulley faces; they operate efficiently at high speeds with minimal noise but are prone to tracking slip under high torque transient loads.
  - **V-Belts:** wedge-shaped for better grip; common in automotive and industrial use
    - Leverage a wedge-shaped cross-section that seats into pulley sheaves, amplifying normal forces via wedging action to transmit higher torques
  - **Timing Belts (Toothed Belts):** have teeth that mesh with pulley grooves; **slip-free motion**
    - Eliminate slip by ensuring positive mechanical engagement between the molded teeth and the pulley grooves. This synchronization is essential in timing applications and closed-loop positioning platforms
  - **Round Belts:** used in light-duty conveyors or spinning machines

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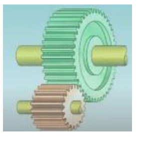
Mechanical Transmission Systems
Industrial Gearbox Classifications

Gearboxes are essential to modify speed and torque profiles while altering the moment of inertia reflected back to the motor shaft. The selection of gearbox type is determined by factors such as torque transmission, size constraints, efficiency, backlash, and load dynamics

The core industrial configurations of gearboxes used in electromechanical systems include:

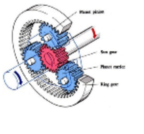
- **Spur Gearboxes**
  Feature parallel shafts and straight-cut teeth. They are simple, cost-effective, and efficient at moderate speeds, but generate noise at higher speeds, due to sudden line-contact engagement
- **Helical Gearboxes** *(≈30% market share)*
  Use angled teeth for a smoother, quieter operation than spur gears. They offer better load distribution and are suited for continuous-duty applications
- **Planetary Gearboxes** *(≈44% market share)*
  Features a central sun gear driving multiple planet gears enclosed within an outer ring gear. This coaxial topology distributes the structural load across multiple tooth meshes, offering exceptional torque density, minimal backlash, and high radial load capability within a compact layout. They provide precise control, being used in robotics and automation systems

Spur



Helical **1**

Helical 2



Planetary

* Market share, data from VDMA

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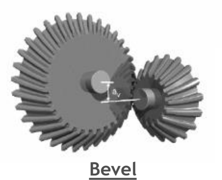
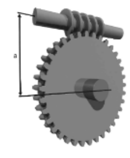
Mechanical Transmission Systems
Industrial Gearbox Classifications

When non-parallel shaft layouts or extreme performance characteristics are required, specialized gearboxes are used

Common types of gearboxes used in electromechanical systems:

- **Bevel Gearboxes (≈17% market share)**
  Employ conical gear geometries to translate rotational power through right angles (typically 90º) inside space-constrained mechanical footprints
- **Worm Gearboxes (≈9% market share)**
  Pair a screw-like worm with a worm wheel to achieve substantial single-stage reduction ratios. They can be designed to be self-locking, preventing the load from back-driving the motor. However, high sliding contact drastically reduces their mechanical efficiency under continuous duty cycles
- **Harmonic Drive Gearboxes**
  Leverage elastic deformation mechanics via a flexible splined cup (flexspline) deformed by an elliptical plug (wave generator) inside an outer circular spline. This design achieves massive reduction ratios with zero backlash, making it a critical component in high-precision robotics


Bevel


Worm


Harmonic Drive

* Market share, data from VDMA

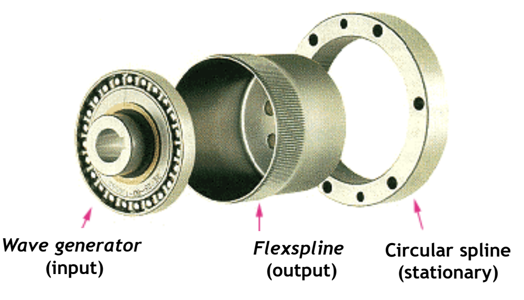
Mechanical Transmission Systems
Harmonic Drive Gearboxes

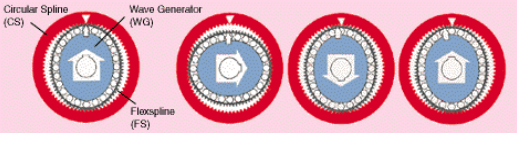
$$\text{Reduction Ratio} = \frac{N_f}{N_c - N_f}$$

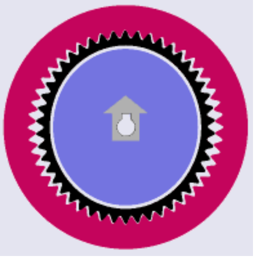
N_f = nº teeth of flexspline

N_c = nº teeth of circular spline

Typical Reduction Ratios:
50:1, 80:1, 100:1, 120:1, 160:1







video

www.harmonicdrive.de

https://harmonicdrive.de/en/technology/

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Mechanical Transmission Systems
Gearboxes - Selection

Characteristics to consider for selection

- Type of gearbox
- Reduction ratio
- Relative position input/output axis
- Output torque (nominal, maximum)
- Max input speed
- Backlash
- Moment of inertia
- Torsional stiffness
- Efficiency
- Weight and size

Selecting a gearbox requires managing complex trade-offs between reduction ranges, thermal efficiencies, spatial configurations, and backlash tolerances

TP+

SK+

See servo gearboxes on: alpha.wittenstein.de

VH+

gearboxes from alpha.wittenstein.de

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Mechanical Transmission Systems
Gearboxes - Comparison

Type	Ratio range	Efficiency*
Spur	up to 6:1	40-98%
Planetary	up to 100:1	Up to 95%
Helical	up to 3500:1	90-94%
Bevel	up to 3000:1	93-97%
Worm	up to 75:1	50% to 98%
Harmonic drive	up to 320:1	Up to 90%

* Values dependent on transmission ratio, number of stages, speed, lubricant, temperature, and power involved

Gearboxes (lenze.com) Roy Mech - RoyMech.org www.harmonicdrive.de

Mechanical Transmission Systems
Reflected Inertia and the Mechanical Optimization Interface

- To optimize the dynamic tracking response of an electromechanical system, the load's physical properties must be analytically reflected back to the motor's rotor shaft. For a rotational system connected through a transmission stage with an exact gear ratio i ($i = \omega_{input}$ / ω_{output}) and a mechanical efficiency parameter η, the reflected moment of inertia J_{load}^{motor} seen by the motor is defined by the following relation:

$$J_{load}^{motor} = \frac{J_{load}^{load}}{i^2 \cdot \eta}$$

- The total mechanical inertia J_{total} that the motor must accelerate is:

$$J_{total} = J_{motor} + J_{gearbos}^{motor} + J_{load}^{motor}$$

- For high-dynamic performance, designers strive for an inertia ratio J_{load}^{motor} / J_{motor} close to 1:1

  If this ratio exceeds 10:1, compliance and torque disturbances can easily cause control loop instability and severe resonance

Mechanical Transmission Systems
Torsional Stiffness and Mechanical Resonance

Every transmission component possesses finite **torsional stiffness** (K_t), behaving mechanically like a torsional spring wrapped in parallel with structural damping elements. This creates a two-mass resonant system composed of the motor rotor inertia (J_{motor}) and the reflected load inertia (J_{load}^{motor})

- The fundamental mechanical anti-resonant (f_{anti}) and resonant (f_{res}) frequencies are modeled by:

$$f_{anti} = \frac{1}{2\pi}\sqrt{\frac{K_t}{J_{load}^{motor}}} \qquad f_{res} = \frac{1}{2\pi}\sqrt{\frac{K_t\left(J_{motor} + J_{load}^{motor}\right)}{J_{motor} \cdot J_{load}^{motor}}}$$

- If the speed or position loop controller attempts to operate near f_{res}, the system enters violent mechanical resonance, generating severe vibrations, audible screeching, and risking component failure. This resonance strictly limits the maximum allowable gain settings and bandwidth of the control loops

Mechanical Transmission Systems
Backlash Dynamics and Closed-Loop Stability Constraints

- Backlash is the physical clearance, or slack, between meshing gear teeth. When the driving motor reverses its rotational direction, the output shaft remains temporarily stationary while the input shaft rotates through this dead-band zone. This structural discontinuity introduces a non-linear phase lag into the feedback loop

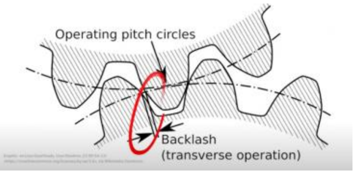

Image ref.

- If the primary position sensor is mounted directly on the load side (full closed-loop control), the controller detects no initial movement during a reversal and continues ramping up its torque command. Once the gear teeth re-engage, the accumulated torque causes a sudden velocity jump, leading to position overshoot, limit-cycle oscillations, and acoustic noise

Mechanical Transmission Systems
Principles and Operation of Electromechanical Brakes

Electromechanical brakes provide controlled stopping torques or secure holding states during emergency stop conditions or power losses. Industrial motion control routinely specifies spring-applied, electrically released brakes for safety considerations:

- **De-energized (Default Safety State):** Internal heavy-duty compression springs push an axial armature plate against friction discs, clamping the rotating shaft securely to the machine frame to prevent movement
- **Energized (Release State):** An electromagnetic coil generates a magnetic flux path that overcomes spring force, pulling the armature plate away and freeing the friction disc for continuous rotation

Sizing criteria for an electromechanical brake include

- Supply voltage and current: account for both **inrush (start-up)** and **holding (maintenance)** current requirements
- Braking torque and load inertia
- Operating time (Engagement/Release)
- Mounting Options
- Manual Release Capability
- Motor and driver compatibility

see electric brakes from: www.warnerelectric.com
SEW

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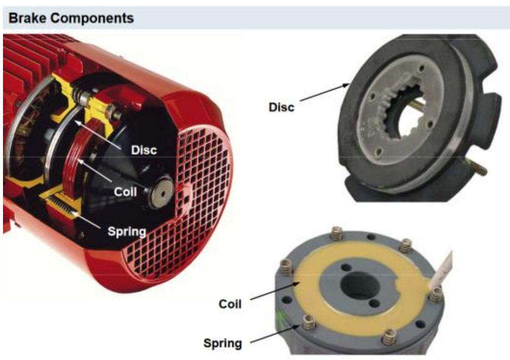
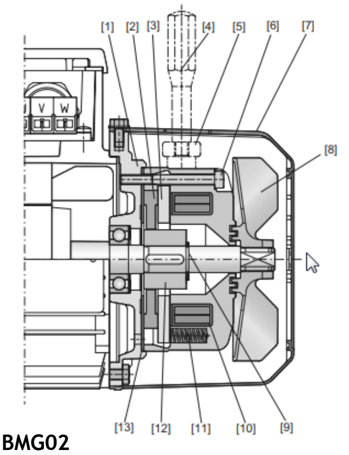
Mechanical Transmission Systems
Electromechanical Brakes

Disc brake with electric actuation, from SEW (sew-eurodrive.com)



[1] Brake endshield
[2] Brake disc (complete)
[3] Pressure plate
[4] Hand lever
[5] Release lever
[6] Retaining screw
[7] Fan guard

[8] Fan
[9] Circlip
[10] Brake coil
[11] Brake spring
[12] Driver
[13] Friction plate



Brake BMG02

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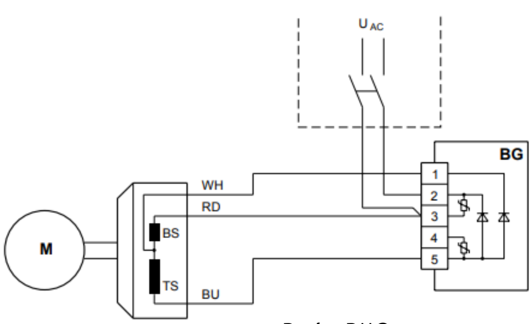
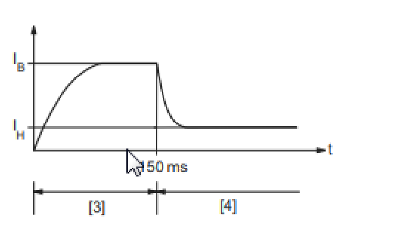
Mechanical Transmission Systems
Electromechanical Brakes

Electric actuation of brake



Brake BMG
sew-eurodrive.com



Mechanical Transmission Systems
Clutches

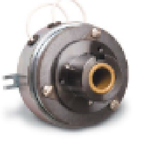
Electromagnetic Clutches are used to **connect or disconnect elements of the drivetrain** during operation, enabling controlled transmission of torque without stopping the motor

Main Types of Electromagnetic Clutches:

- **Positive-Type Clutches (Tooth Clutches):**
  - Feature interlocking teeth for direct, slip-free torque transmission
  - Can only be engaged at standstill or when synchronized (at very low relative speeds)
  - Ideal for applications requiring high torque transmission with precise engagement

Tooth clutch, from KEB video

- **Friction-Type Clutches:**
  - Torque is transmitted via **friction surfaces** pressed together when the clutch is energized.
  - Can be engaged at **higher relative speeds**, depending on the required torque and system design
  - Suitable for applications where **smooth engagement** and **slip tolerance** are important



Shaft Mounted Clutches, friction type, from Electromate

www.electromate.com

Mechanical Transmission Systems
Shaft Alignment and Mechatronic Couplings

Perfect coaxial alignment between two independent shafts is practically impossible due to assembly tolerances, thermal growth, and structural deflections under load. Standard mechanical couplings manage these non-idealities across three profiles: parallel offset, angular deviation, and axial end-play

- **Rigid couplings** deliver maximum torsional stiffness but require precise alignment to prevent high radial forces from overloading shaft bearings.

- **Flexible couplings** (e.g., bellows, jaw, disc types) use compliant elements to isolate misalignments while maintaining torsional stiffness

- **Modern instrumented couplings** integrate wireless telemetry arrays to monitor torque, velocity, acceleration, and angular position in real time.

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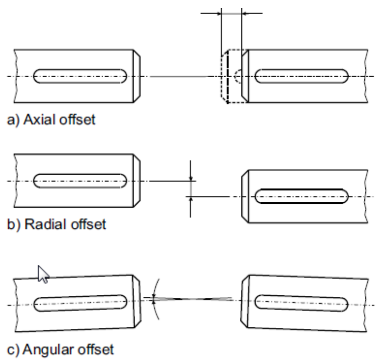
Mechanical Transmission Systems
Shaft Alignment and Mechatronic Couplings

Problem of shaft misalignment



- **Flexible coupling**



high torsional rigidity **lower torsional rigidity**

- **Rigid coupling**

www.rw-couplings.com
www.ruland.com
www.huco.com

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Mechanical Transmission Systems
Shaft Alignment and Mechatronic Couplings

Instrumented coupling with wireless network communication

- Monitoring:
  - Torque
  - Speed
  - Acceleration
  - Rotation and special position

www.rw-couplings.com/sensor-technology/

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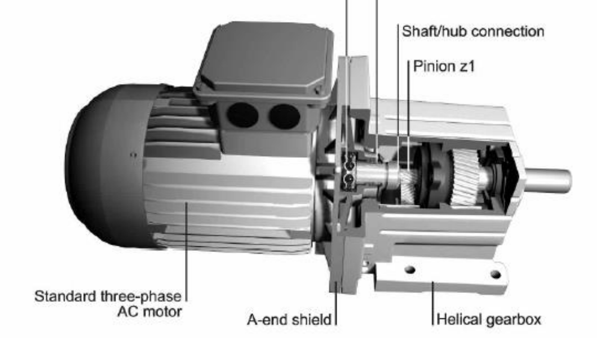
System Integration
Gearmotor (Motor + Gearbox)

Type of gearbox / Type of shaft	Helical gearbox (Solid shaft and shaft mounted)	Bevel gearbox and worm gearbox	Planetary gearbox
Solid shaft	 coaxial	 angled	 coaxial
Hollow shaft	 axial	 angled	end-to-end hollow shaft not possible

Gearmotors from SEW

Gearmotors from SIEMENS



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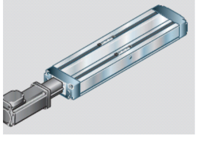
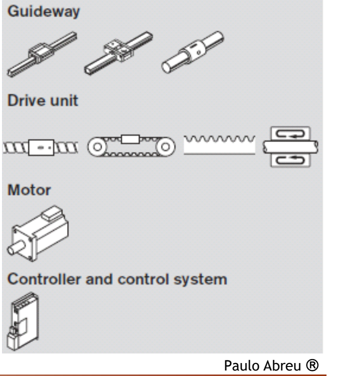
System Integration: Pre-Engineered Linear Actuation Axes

Modern machine design often replaces component-by-component assembly with pre-engineered linear modules. These integrated assemblies bring together four foundational elements within a standardized structural enclosure:

- Anodized Structural Frame: Serves as the precise mounting backbone for the axis
- Linear Precision Guiding Rails: Configured to handle vertical forces and multi-axis moment loads
- Kinematic Conversion Core: Leverages either a high-rigidity ball screw or a high-velocity timing belt assembly
- Motor-Drive and Adapter Interface: A structured flange designed for plug-and-play mounting of servo or stepper systems



www.boschrexroth.com



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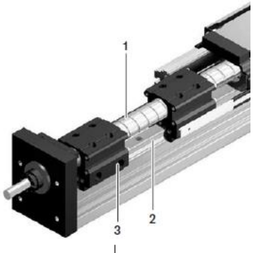
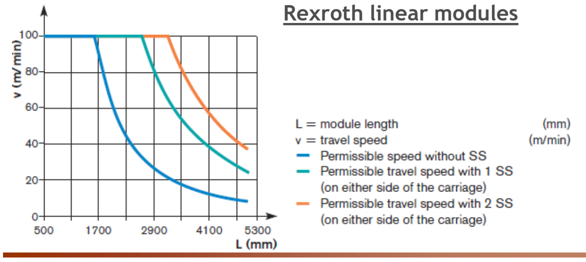
Linear Actuation Axes: Model MKK from Rexroth

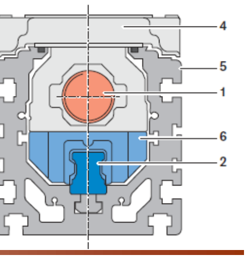
- **Model MKK**
  - Ball screw and ball slide rail
  - Operating speed dependent on stroke and fastening method
  - Load capacity dependent on guide size
  - Distinct lead of ball screw (2, 5, 10, 16 ,20 32 40 mm)



Rexroth linear modules



1 - ball screw
2 - rail
3 - ball screw support
4 - carriage
5 - structure
6 – runner block *(patim de esferas)*



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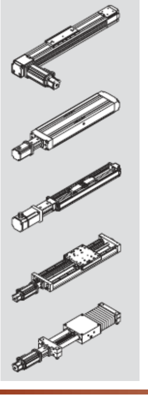
Linear Actuation Axes

Multiple configurations

www.boschrexroth.com



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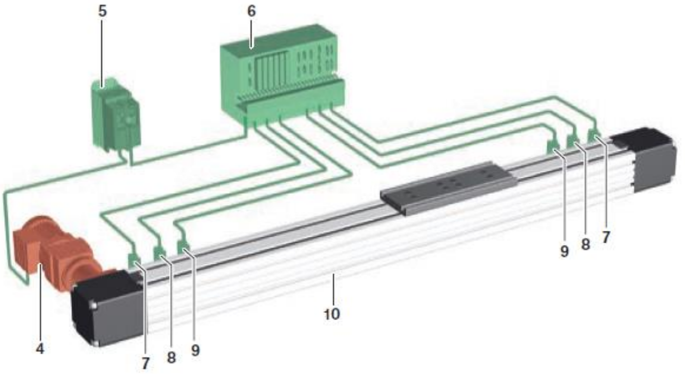
Linear Actuation Axes: Typical Configuration



4. Motor
5. Driver motor
6. PLC
7. 8. e 9 limit switches
10. Linear module

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Spatial Configurations of Multi-Axis Positioning Modules

Individual linear axes can be combined to build multi-dimensional positioning configurations:

- Cartesian Coordinate Systems: Formed by rigidly stacking independent orthogonal linear axes (e.g., X-Y-Z configurations) where each axis handles its own directional vector

- Gantry System Configurations: Feature parallel base axes (X and X´), mechanically synchronized or driven by independent dual-loop control software to move a large spanning gantry beam

These setups are widely used across industrial pick-and-place robotics, automated assembly cells, heavy-duty CNC machining centers, and additive manufacturing platforms

Boschrexroth multi-axis systems

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Metrology, Feedback, and Closed-Loop Control Architecture

Feedback and measurement devices are critical for **monitoring motion parameters** (position, speed, torque, etc.) and providing real-time data to control systems. **Closed-loop motion control** relies on continuous, high-speed feedback states to adjust voltage and current commands. Sensors translate raw physical attributes (such as angular position, linear speed, or winding temperature) into electrical signals compatible with microcontrollers and PLCs

- **Main Feedback and measurement devices include**
  - Angular Position Measurement, incremental or absolute measure
  - Linear Position Measurement, incremental or absolute measure
  - Speed Measurement
  - Temperature Measurement
  - Proximity and Limit Detectors
  - Current Measurement
  - Power Measurement
  - Other Sensors and Detectors
    - Load cells: for force/weight measurement
    - Inertial Measurement Units (IMUs)
    - Vibration sensors

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Angular Position Measurement Devices

- **Devices**
  - Encoders
  - Sin-cos encoder
  - Resolver
  - Potentiometers
  - LVDTs
- **Technology used**
  - Optical
  - Magnetic
  - Inductive
  - Resistive

Measurement of absolute position or relative position (incremental encoder, ex.), Digital or analog outputs

Heideneim incremental encoder ERN 400 Series

Maxon Resolver Res 26

Angular Position Measurement Devices
Encoders and Resolvers

Encoders

- Encoders are electromechanical sensors that convert the **rotational position** of a shaft into an **electrical signal** (digital or analog) that a controller can interpret
  - **Digital Encoders** provide a Digital Code output
    Utilize two phase-shifted optical channels (A and B) to generate square-wave pulses. By counting pulse edges, the drive determines relative position, while the phase shift indicates direction via quadrature decoding. A distinct index pulse (Z) provides a physical home reference
  - **Sin-Cos Encoders** provide an Analogue Signal output
    Output high-fidelity analog sine and cosine waves rather than digital pulses. The drive interpolates these signals to achieve ultra-fine resolution measurements for smooth speed regulation at low velocities

Resolvers

- Resolvers function as rugged, analog rotary transformers. They consist of a primary rotor winding energized by a high-frequency AC reference voltage ($V_{ref} = V_0 \sin(\omega\, t)$), which inductively couples to two stationary stator windings oriented at an orthogonal 90º angle. The resulting output voltages are modulated by the mechanical shaft angle (θ):

$$V_{\boldsymbol{sin}} = V_0 \cdot \boldsymbol{K} \cdot \sin(\boldsymbol{\omega}\, t) \cdot \sin(\boldsymbol{\theta}) \qquad V_{\boldsymbol{cos}} = V_0 \cdot \boldsymbol{K} \cdot \sin(\boldsymbol{\omega}\, t) \cdot \mathbf{cos}(\boldsymbol{\theta})$$

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Angular Position Measurement Devices
Encoders and Resolvers

- An external resolver-to-digital converter (RDC) processes these analog signals to extract the absolute angular position via an arctangent calculation $\theta = \arctan(V_{sin} / V_{cos})$. Lacking glass disks or sensitive electronics, resolvers operate reliably under extreme shocks, severe vibrations, and high temperatures.

Feature	Encoders	Resolvers
Signal Type	Digital (or analog for sine-cos)	Analog sine-cos
Resolution	High (up to 24-bit)	Moderate (depends on converter)
Power-Off Retention	Absolute types: Yes	Yes (with proper conditioning)
Environmental Robustness	Moderate to high (depends on type)	Very high (vibration, temperature)

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Angular Position Measurement Devices
Communication Interfaces: SSI, BiSS-C, and SPI

Modern absolute **encoders** transmit high-resolution multi-turn position codes over specialized serial communication interfaces to minimize wire counts and prevent signal corruption from industrial electromagnetic noise:

- **SSI (Synchronous Serial Interface):** A classic point-to-point master-slave protocol using balanced differential clock and data lines
- **BiSS-C (Bidirectional Serial Synchronous - Continuous):** An open, high-speed real-time interface that permits continuous synchronous data rates up to 10 Mbit/s, sending position updates matching the control loop's cycle time
- **SPI (Serial Peripheral Interface):** A standard short-distance bus format used primarily for direct board-to-board communication inside compact, integrated servo drives

Example: PA0260 General-purpose encoder PCB that can be mounted on all kinds of stepper or servomotor.

- **Incremental or absolute multi-turn encoder with incremental ABZ signals, sin/cos signals, or SSI or BISS-C interface. Resolution from 128 to 65536 cnt/rev.**
- **Factory programmed Resolution of 128, 256, 512, 1024, 2048, 4096, 8192, 16384 cnt/rev.**
- **Up to 16-bit interpolated resolution 32768, 65536 cnt/rev.**
- **Integrated RS422 transceiver up to 10 Mbit/s, 5V to 30V supply and signals**
- **Absolute resolution of 0.02° (14 bit / 360° at up to 10000 rpm)**

www.jvl.dk/1168/pa0260-encoder

Angular Position Measurement Devices
Potentiometers

- Potentiometric transducer
  - Absolute position measurement
  - Simplest displacement transducers and low cost
  - Composed of a winding of conductive wire and a movable contact attached to the moving object
- Working principle
  - Resistance is proportional to linear/angular displacement
  - Voltage Divider Principle
- Drawbacks
  - Wear
  - Fragile
  - Limited measuring range

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Linear Position Measurement Devices

Direct linear position measurement avoids accuracy errors caused by transmission backlash and thermal changes in screw element

Main measuring devices

- Linear encoders (ex. heidenhain linear encoders)
- Inductive linear Sensors (ex. pepperl-fuchs inductive positioning systems)
- Magnetic Linear Sensors (ex. SIKO MagLine linear sensor)
- Inductive positioning systems)
- Inductosyn - working principle similar to synchro resolver
- LVDTs (Linear Variable Differential Transformer)
- Linear Potentiometers (ex. Video on working principle)

Heidenhain video

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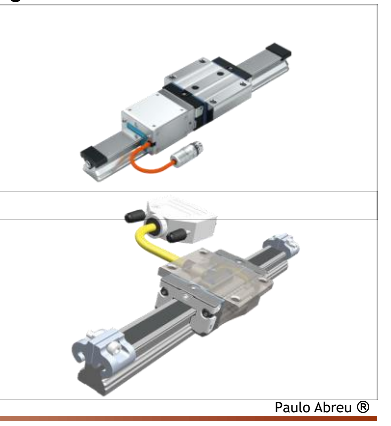
Linear Position Measurement Devices
Integrated Systems for Linear Axis

Integrate inductive or magnetic scale patterns directly onto the mechanical linear guide rail. A compact reader head mounted on the moving runner block decodes positions in real time as it glides along the rail.

- Integrated measuring systems IMS
  - Measuring principle: inductive
  - Variant incremental, absolute
  - Machine tools, axes with a linear motor
- Integrated measuring systems IMScompact
  - Measuring principle: magnetic
  - Variant incremental, absolute (in preparation)
  - Automatic positioning, handling, and axes with a linear motor
  - More economical compared to IMS inductive



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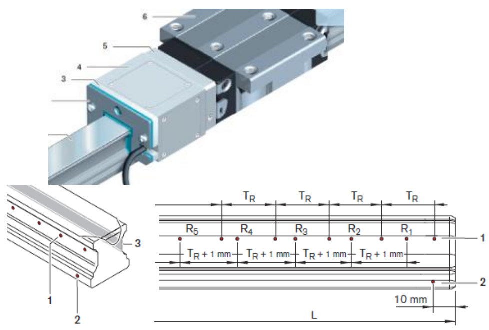
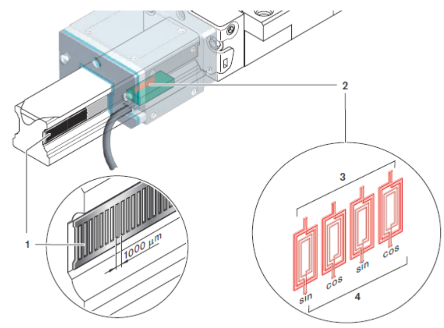
Linear Position Measurement Devices
Sin-Cos Encoder for Linear Axis

Roller rail system with integrated position measurement system

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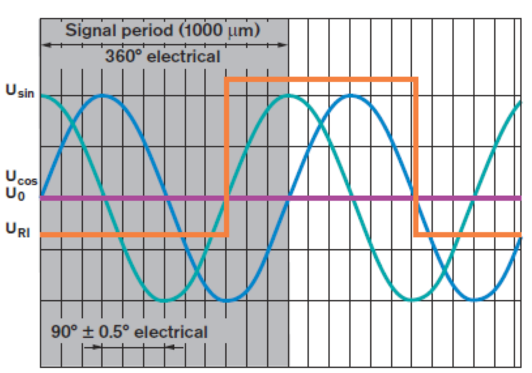
Linear Position Measurement Devices
Sin-Cos Encoder for Linear Axis

Electronics can provide an analog signal and digital outputs (encoder type)



U_{sin}/U_{cos} Sinusoidal voltage signals
U_0 Passage through zero
$U_0 = 2.5\ V \pm 0.5\ V$
U_{RI} Reference mark signal

$$\text{Resolution} = \frac{\text{scale pitch}}{\text{evaluation} \cdot \textbf{factor}}$$

Factor	Resolution
25x	10 µm
50x	5 µm
256x	1 µm
1024x	0.25 µm

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Linear Position Measurement Devices
Sin-Cos Encoder for Linear Axis

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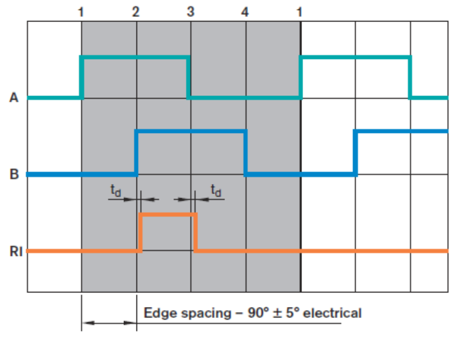
- After interpolation, the measurement system provides digital outputs (square wave, TTL levels). Possible resolutions are 0.25 µm, 1 µm, 5 µm and 10 µm
- The interpolation accuracy is identical for all resolutions and is +/- 3 micron
- The repeatability of the position measurement is dependent on the chosen resolution



Resolution with TTL signal	µm	0.25	1	5	10
Repeatability	µm	2	2	5	10

A/B Incremental TTL square-wave signals
RI Reference mark signals
t_d Time delay $|t_d| < 0.1$ µs

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Position Measurement Devices - Comparison

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Position measuring system	Compatibility with coolants	Insensitivity to shavings	Dry processing	Space requirement	Mounting
Optical	o	o	++	+	++
Magnetic	+	o	++	+++	+++
Inductive	+++	+++	+++	+++	+++

Position measuring system	Retrofitability	Design	Accuracy class	Resolution Repeatability
Optical	o	o	+++	+++
Magnetic	++	+++	+	+++
Inductive	+++	+++	++	++

+++ Very good ++ Good + Satisfactory o Adequate

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Position Measurement Devices - Selection

Main aspects to consider:

- Transducer type, linear or rotary
- Incremental, absolute, one-turn, or multi-turn measurement
- Electronics for processing information, whether incorporated or external
- Output interface (digital, analog), discrete, or communication protocol
- Resolution and accuracy
- Maximum operating speed, environmental conditions, mechanical assembly, and mechanical robustness
- Electrical power requirements

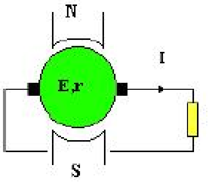
Speed Measurement Devices
Tachogenerator

Tachogenerator

- **Working principle**
  - Analog output: generation of a voltage proportional to the rotation speed (direct current generator)
  - Constant-induced magnetic field generated by permanent magnets
  - Typically low-value output voltage (example 20V @1000rpm - WEG TCW20)
- **Drawbacks**
  - Collector brush wear, long-term degaussing

Note 1: The resolver can also function as an analog speed transducer

Note 2: There are digital sensors for speed measurement (pulse count per unit of time)



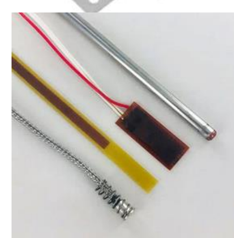
www.tachogeneratorsguide.com RDC207/208

Temperature Measurement Devices (I)

Continuous temperature monitoring protects motor insulation from thermal degradation and alerts systems to persistent overloads

Resistance Temperature Detectors (RTDs)

- **RTDs** are precision, wire-wound resistors or thin-film elements made from materials (typicall platinum) with well-defined resistance-temperature relationships
- **Operating principle**: variation of resistivity as a function of temperature
- **RTDs installation in electric motors**:
  - in the slot portions of the stator windings of **Form-wound motors**
  - placed either in the slots (standard configuration) or in the end turns for localized temperature monitoring, in **Mush-wound motors**
- **RTDs electrical connection:** RTDs are commonly integrated into a Wheatstone bridge circuit, accurately measuring the small resistance changes corresponding to temperature variations. The output of this circuit can be used to drive a temperature-calibrated meter or to operate a relay to sound an alarm or shut down the motor. Typically, a Transmitter is used to connect an RTD to a PLC
- **Advantages of RTDs:** High accuracy and stability over time. Good repeatability. Suitable for continuous monitoring in **industrial motors and drives**



RTDs probes

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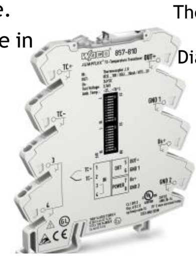
Temperature Measurement Devices (II)

Thermocouple

- **Operating Principle:** based on the **thermoelectric effect**. When two dissimilar metals are joined to form a junction and that junction is exposed to a different temperature than the other ends (known as the cold or reference junction), an electromotive force (EMF) is generated. This EMF is a function of:
  - **Metal Composition:** The specific metals used determine the sensitivity and range.
  - **Temperature Difference:** The voltage output is directly related to the difference in temperature between the hot junction and the cold junction
- **Common Types of Thermocouples**:
  - T, J, E, K, R, S
- **Signal Conditioning Requirements:**
  - **Amplification**, **Cold-Junction Compensation**, and **Filtering and Linearization** (see video)

see video on thermocouple

RS PRO Type J Thermocouple 20mm Length, 5mm Diameter → +400°C



WAGO857-810 JUMPFLEX® signal conditioner; temperature; thermocouples of type J, K; configurable

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Proximity and Position Sensors (I)

Digital Detection Sensors provide binary ON/OFF signals to indicate presence, manage safety boundaries, or establish zero-point reference positions.

These sensors incorporate intentional electrical hysteresis, with the activation and deactivation points physically separated, to prevent rapid, unstable switching caused by mechanical vibrations.

- Common industrial technologies include non-contact inductive sensors for metallic targets, capacitive sensors for non-metallic items or fluids, photoelectric beams for long-range detection, and physical electromechanical limit switches for high-reliability contact safety lines

- The **choice** of **transducer technology** depends on
  - Material or object to detect
  - Detection distance
  - Object Size
  - Environment Conditions

- **Characteristics**
  - Shape/Envelope
  - Reach
  - Degree of protection
  - Connections
  - Power requirements

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Proximity and Position Sensors (II)

Common Technologies Used in Digital Detection Sensors

- Inductive sensors: Detect metal objects without contact.
- Capacitive Sensors: Detect any material, including plastic, glass, or liquid, without contact
- Ultrasonic Sensors: Detect hard or transparent materials or irregular shapes, without contact.
- Photoelectric Sensors: Use a light beam to detect objects; available in through-beam, retro-reflective, or diffuse types, without contact.
- Magnetic and Reed Switches: Electronic switch (Hall effect) or Electromechanical switch triggered by magnetic fields, without contact
- Limit switch: An electromechanical switch triggered by physical contact

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Proximity and Position Sensors (III)

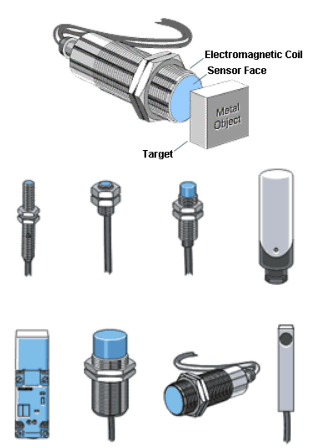
Contactless Proximity detectors	Detectable objects	Technology
Inductive	Metallic	Electromagnetic field
Capacitive	Any	Electrostatic
Ultra-sonic	Any	Sound waves
Photo-electric	Any	Light

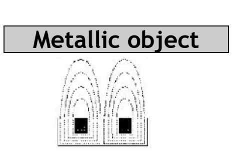
Inductive Sensor Interfaces and IO-Link Architecture

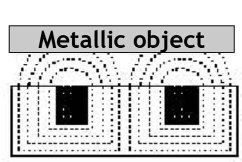
Function: Non-contact detection of metallic objects.

Working principle

- The sensor generates an **oscillating magnetic field.** When a metallic object enters this field:
  - It **disturbs the magnetic field**, inducing **eddy currents** in the object
  - This causes a **change in the amplitude** of the sensor's oscillations
  - The sensor detects this change and triggers a **switching signal**



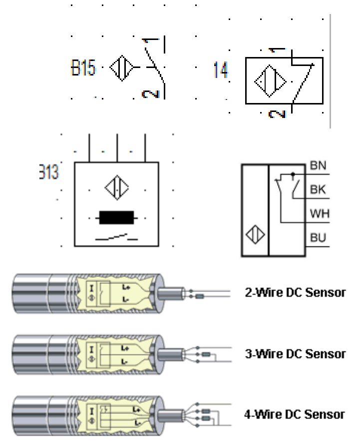




Inductive Sensor Interfaces and IO-Link Architecture (II)

Electrical Characteristics and Output Options

- **Power Supply:** Typically **DC-powered** (e.g., 10–30 VDC)
- **Wiring Configurations:** Available with **2-wire**, **3-wire**, or **4-wire** setups, depending on the application and output type:
  - 2-wire: Simplified connection (typically current switching)
  - 3-wire: Common for most DC sensors (Power, Ground, Signal)
  - 4-wire: Dual outputs or advanced communication features
- **Output Transistor Types:**
  - **PNP** (Sourcing Output) dominant standard in Europe, and **NPN** (Sinking Output), widely used across Asian automation markets
- **IO-Link Compatibility:**
  - Modern premium sensors update the point-to-point 3-wire interface with digital IO-Link protocols. This enables bidirectional data transmission, permitting remote parameter updates and field status monitoring



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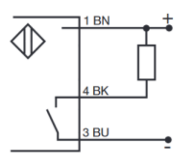
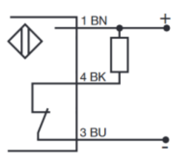
Inductive Proximity Sensors (III) Connection diagrams

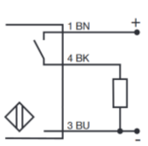
Connection diagrams



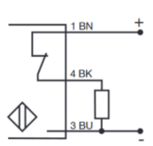
NPN normally open



NPN normally closed

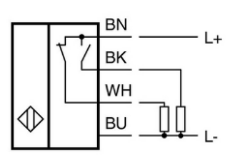


PNP normally open

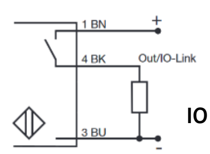


PNP normally closed

Proximity detector from Carlo Gavaazzi, **ICB12, ICB18 & ICB30 IO-Link 3-wire DC**



4-wire **connections**



IO link

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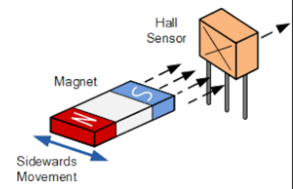
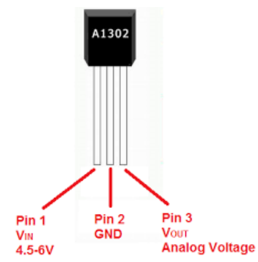
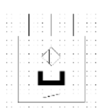
Magnetic Threshold Transducers: Hall Effect Sensors and Reed Switches

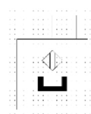


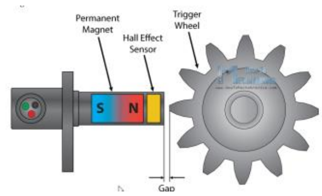
Operating Principle:

- The **Hall Effect** is based on the **generation of a voltage (Hall voltage)** across a semiconductor material when it is placed in a **magnetic field,** and a current flows through it. This voltage is **proportional to the strength of the magnetic field**
- **Key Applications:**
  - **Proximity detection** – Detecting the presence of a magnetic target (e.g., magnets on rotating parts)
  - **Position sensing** – Linear or angular displacement measurement
  - **Current sensing** – Measuring current indirectly by detecting the magnetic field generated around a conductor









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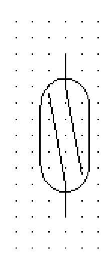
Reed Switches

Operating Principle:

- A **reed switch** comprises two thin **ferromagnetic metal reeds** sealed inside a small glass tube. When exposed to a **magnetic field**, the reeds become magnetized and **attract each other**, closing the circuit. Once the magnetic field is removed, the reeds separate, and the circuit opens. Operates as a electromechanical switch but is operated by the detection of a magnetic field

Key Characteristics:

- Activated by proximity to a magnet
- Non-contact switching, ideal for simple and reliable detection
- Mechanically simple and low-cost
- Very low switching capacity (typically only for low-voltage, low-current applications)



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Edge Diagnostics and System Monitoring

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Transitioning from scheduled maintenance to predictive maintenance and performance optimization requires continuous monitoring of operational parameters to catch failures before they cause system breakdowns. Data collection systems track parameters across distinct operational regimes:

- **Power and Energy**: evaluating efficiency and detecting overloads. This helps in understanding the energy consumption patterns, optimizing power usage, and identifying winding insulation degradation or phase imbalances
- **Kinetic and Mechanical Regimes:** High-frequency vibration sensors identify bearing failures, shaft misalignments, or gear tooth wear. The use of MEMS (Micro-Electro-Mechanical Systems) or piezo sensors is common
- **Thermal Regimes:** Monitoring temperature trends provides an early warning of lubrication breakdown or structural overload

Electrical Analytics: Power Meters and Current Probes

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Non-intrusive electrical sensing monitors system loads without requiring inline wiring changes

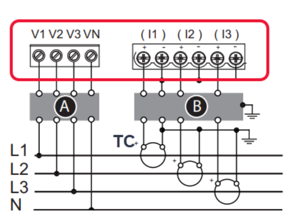
Power Quality Meters: Combine current and voltage signals to calculate real-time electrical metrics, including active power, reactive power, power factor, and total harmonic distortion (THD)

Power meter main functions

- Monitoring voltage, current, power (active, reactive), power
- Energy Consumption Monitoring
- Frequency Measurement
- Programmable digital inputs/outputs
- Data Logging and Analysis
- Alarms (over/under current or voltage)
- Ethernet connection for data logging
- Use of **current transformers** (CT) to measure line currents

CT

Power meter



METSE PM5100

See Schneider Power Metering and Energy Monitoring Systems

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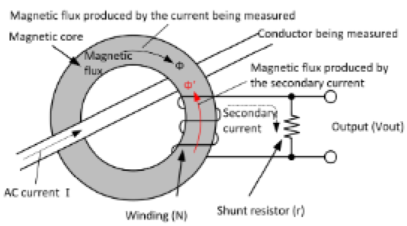
Electrical Analytics: Power Meters and Current Probes

- Current probes are versatile tools for measuring both AC and DC currents without interrupting the circuit
- Main type of current probes
  - Current transformer (CT) probes, for AC currents (ref)
  - Hall Effect Current Probes, for AC and DC currents (ref)
  - Rogowski Coil Probes, for AC currents (ref)



For AC currents

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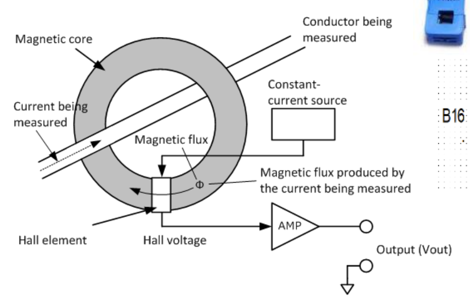

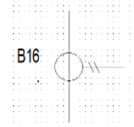

For AC and DC currents

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Motor Condition Monitoring Devices (I)

- Modern condition monitoring combines multi-sensor arrays with dedicated edge-computing hardware. Compact smart sensor nodes are mounted directly to motor frames to continuously capture temperature, multi-axis vibration, and acoustic signatures
- These devices use internal microcontrollers to run fast Fourier transforms (FFT), converting raw vibration signals into frequency spectra. Spikes at specific frequencies reveal precise failure modes, such as inner bearing race defects or unbalances, allowing systems to flag maintenance needs via industrial network buses before failures happen
- Examples from Omron, ABB, and Siemens

Motor Condition Monitoring Devices (II)

Devices to monitor a three-phase induction motor or servomotors for identifying failure modes, detecting defective parts, and ensuring efficient operation

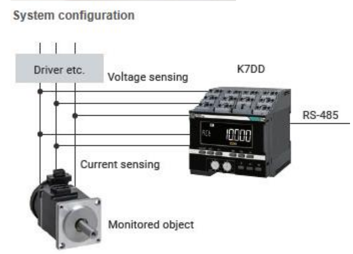
Main functions

- Identification of failure modes and defective parts of motor equipment
- Motor current and voltage monitoring
- Vibration and temperature monitoring (requires external sensors)
- Implementation of scheduled maintenance activities with real-time condition monitoring of motors such as servo motors and induction motors that frequently change speed
- Compatible with the use of VFDs
- Data Logging and Analysis

Example: Omron K7DD, Omron K6CM

eMotor condition monitoring device

Omron K7DD



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Motor Condition Monitoring Devices (III)

- ABB smartsensor
- Siemens SIDRIVE IQ

Sensors to be incorporated in motors, with temperature and vibration measurement, for continuous evaluation of the state of the motor

- Wireless communications, for cloud connection
- Applicable to any motor
- Real-time data
- AI-Based Monitoring
- Predictive maintenance
- Element of Industry 4.0

See video1 video2

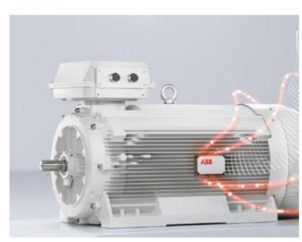
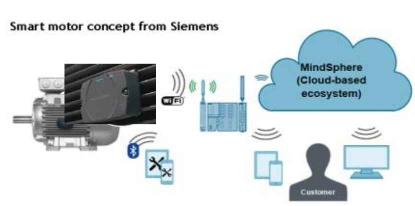


ABB smartsensor



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Conclusions

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- **Holistic System Design is Crucial**
  - Optimal performance comes not just from efficient motors but from the synergistic integration of mechanical structure, transmission elements, feedback systems, and control strategy
- **Impact of Mechanical Design on Efficiency**
  - Mechanical design factors, such as material selection, component geometry, mechanical guiding systems, and assembly techniques, affect the energy consumption and torque requirements of electrical motors. Using lightweight materials and optimizing design to reduce friction and wear can enhance efficiency
- **Mechanical Guiding Ensures Precision**
  - Linear and rotary guides minimize friction, maintain alignment, and enable precise motion control
- **Transmission Adapts Motion and Power**
  - Gearboxes, screws, belts, and couplings tailor motor output to the application's speed, torque, and direction requirements and have an impact on energy efficiency
  - Gearboxes are crucial for power transmission efficiency. Efficient design involves selecting the right gear type and optimizing load capacity, material selection, and lubrication strategies

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Conclusions

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- **Feedback Devices Enable Control and Intelligence**
  - Devices like encoders, resolvers, potentiometers, and LVDTs provide real-time data for closed-loop control, essential for accuracy, repeatability, and diagnostics
- **Optimizing Feedback and Control for Energy Savings**
  - Optimizing feedback and control systems can lead to significant energy savings. Implementing real-time monitoring and advanced control algorithms helps reduce energy waste and improve system performance
- **Condition Monitoring Improves Reliability and Reduces Downtime**
  - Real-time monitoring of current, power, temperature, and vibration supports predictive maintenance and extends system lifespan
- **Predictive Maintenance Strategies**
  - Predictive maintenance uses data-driven insights to foresee equipment failures, optimizing asset longevity and operational efficiency. Continuous monitoring and advanced analytics help identify issues early and schedule maintenance activities accordingly

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