BASICS OF MECHATRONICS

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KOMAG

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1 INTRODUCTION

Mechatronics represents an interdisciplinary branch of engineering that synergistically integrates mechanical systems, electronics, control engineering, and computer science into one functional whole. This approach enables the creation of intelligent products and systems that would not be possible to realize using conventional methods with individual disciplines working separately.

Key concepts defining mechatronics include several fundamental aspects. Synergy means that the resulting system has properties and capabilities that individual disciplines cannot provide independently. Integration of multiple disciplines enables solving problems in a comprehensive manner, where mechanical, electrical, and software solutions mutually complement and compensate for their shortcomings. The interdisciplinary character requires engineers to have the ability to work and communicate across traditional disciplinary boundaries. The design philosophy of mechatronic systems differs fundamentally from sequential development. The traditional approach often begins with mechanical design, then electronics for sensing and actuation are added, and finally software for control. This sequential approach can lead to suboptimal solutions because each phase is constrained by decisions from previous phases. In contrast to this approach, mechatronic design begins with simultaneous analysis of all aspects of the system, which allows finding a global optimum instead of local optimizations of individual subsystems. Intelligent systems with embedded control represent the practical realization of mechatronic philosophy. These systems contain an embedded computer that continuously monitors the system state through sensors, evaluates measured data according to control algorithms, and generates control actions realized through actuators. This closed-loop approach with feedback enables the system to adaptively respond to environmental changes, compensate for disturbances, and achieve desired behavior even in the presence of uncertainties and imprecisions. The mechatronic approach (Fig. 1) brings numerous concrete advantages over the traditional approach.

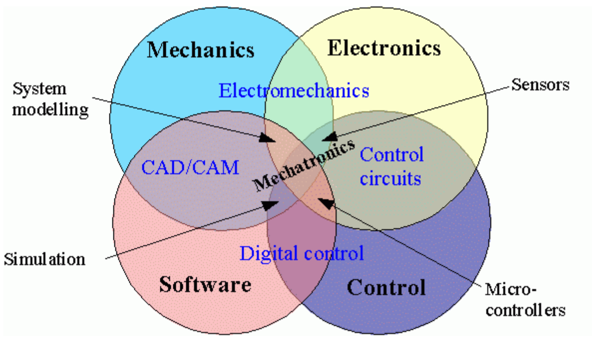

Fig. 1 Synergistic integration of disciplines in mechatronics

Systems are more compact because functions previously realized mechanically can be replaced by software solutions. Higher precision is achieved thanks to the possibility of compensating mechanical imprecisions through precise sensors and control algorithms. Systems are more flexible because a change in system behavior can often be achieved only by changing software without the need for physical modifications. Reliability increases because complex mechanical mechanisms prone to wear are replaced by electronic solutions with minimal wear.

A fundamental aspect of mechatronic systems is the feedback between the physical system and the control algorithm. The mechanical system creates physical processes that are monitored by sensors. Sensors provide information about the current system state to the control unit. The control unit evaluates this information, compares it with the desired state, and calculates necessary control actions. Control actions are realized by actuators that act back on the mechanical system. This closed cycle repeats with high frequency, typically tens to thousands of times per second, which enables the system to dynamically respond to changes and achieve desired behavior.

The key to effective functioning of this cycle is proper design of all its components and their mutual interaction. The mechanical system must be designed considering the capabilities and limitations of sensors and actuators. Sensors must provide sufficiently precise and fast information for the needs of the control algorithm. The control algorithm must be designed to utilize available information and actuator capabilities in an optimal manner. Actuators must be capable of realizing required control actions with sufficient speed and precision.

1.1 Basic Components

Mechatronic systems are based on the integration of several fundamental types of components that together create a functional whole capable of intelligent behavior. Each of these component types fulfills a specific role within the system, and their mutual interaction defines the overall behavior of the mechatronic system.

The mechanical part of the mechatronic system ensures physical interaction with the world and realizes the required system function. Mechanical components include load-bearing structures, mechanisms for motion transfer, moving parts performing the working function, and interfaces for interaction with objects or the environment. Design of the mechanical part in the mechatronic approach takes into account the needs of sensors and actuators from the beginning, which often leads to simpler mechanical solutions compared to the traditional approach where complex functionality is realized purely mechanically.

In mechatronic systems, the principle of simplifying mechanics by substituting functions with electronics and software is often utilized. For example, instead of a complex mechanical transmission system with multiple speed stages, a simpler mechanism can be used in combination with an electronically controlled motor capable of smooth speed variation. This approach not only simplifies mechanics but often brings additional advantages such as lower weight, less wear, and higher reliability.

Sensors represent the sensory organs of the mechatronic system, which collect information about the system state and its surroundings. NYU Tandon School of Engineering classifies sensors according to several criteria. According to the operating principle, we distinguish active transducers, which require an external energy source

and generate an output signal proportional to the measured quantity, and passive transducers, which directly change their property under the influence of the measured quantity without the need for external power.
According to the type of measured quantity, we distinguish biological sensors for biological processes, chemical sensors for detection of chemical substances and concentrations, electrical sensors measuring voltage and current, electromagnetic sensors for detection of electromagnetic field, thermal sensors for measuring temperature and heat flow, magnetic sensors for measuring magnetic field, mechanical sensors for measuring mechanical quantities such as position, velocity, acceleration, force, pressure and torque, and optical sensors utilizing light for measuring various quantities.
In mechatronic applications, the most frequently used sensors include encoders for measuring position and velocity of rotating parts, position sensors utilizing potentiometers, Hall sensors or magnetic encoders, accelerometers and gyroscopes for measuring acceleration and angular velocities, pressure sensors in hydraulic and pneumatic systems, strain gauges for measuring forces and torques, temperature sensors for monitoring thermal state, proximity sensors for detecting the presence of objects without physical contact, and optical sensors including cameras for visual inspection and recognition.
Selection of a suitable sensor for a specific application requires consideration of several parameters. Measurement range must cover expected values of the measured quantity with sufficient reserve. Resolution determines the smallest detectable change in the measured quantity and must be sufficient for required control precision. Accuracy and repeatability determine to what extent the measured value corresponds to the actual value and how consistent measurements are in repeated trials. Response speed must be sufficient considering the dynamics of the controlled system. Environmental robustness includes resistance to temperature, vibrations, humidity, dust, and electromagnetic interference.
The control unit represents the brain of the mechatronic system, which processes information from sensors, executes control algorithms, and generates control signals for actuators. In modern mechatronic systems, control units are typically based on microprocessors or microcontrollers. Microcontrollers are specialized integrated circuits containing a processor, memory, input-output peripherals, and various auxiliary modules optimized for control applications on a single chip.
For simpler applications with limited computational requirements, single-chip microcontrollers with integrated analog-to-digital converters, timers, communication interfaces, and sufficient memory are sufficient. For more demanding applications requiring higher computational power, faster response, or processing larger amounts of data, more powerful processors are used, often with specialized units for signal processing or floating-point operations. In the most demanding applications such as motion control of industrial robots or CNC machines, specialized motion controllers are used that integrate multiple axes of control, interpolation, and real-time communication with drives.

Actuators represent the executive organs of the mechatronic system that convert electrical signals into mechanical motion or force. In mechatronic applications, the most common are electric actuators in various configurations. DC motors with brushes are simple and cost-effective but have limited lifespan due to brush wear. Brushless DC motors eliminate this problem and offer higher efficiency and longer lifespan. Stepper motors enable precise positioning without feedback sensors. Servo motors provide the highest performance in terms of dynamics and precision. Asynchronous AC motors are suitable for higher powers and continuous operation.

Pneumatic and hydraulic actuators are used in applications requiring high forces or speeds at reasonable cost. Pneumatic cylinders are simple, robust, and cost-effective for linear motion with limited precision requirements. Hydraulic cylinders provide very high forces in compact designs. However, both pneumatic and hydraulic systems require auxiliary equipment such as compressors or pumps, pressure regulation, and piping.

1.2 Industrial Applications

CNC machine tools represent a key industrial application of mechatronics. Computer Numerical Control means that tool movements are controlled by a numerically defined program, as opposed to traditional manual machines. Modern CNC machines are sophisticated mechatronic systems capable of achieving extraordinary precision and productivity.

Key mechatronic techniques in CNC machines include precise position control utilizing cascaded control with an inner current control loop, middle velocity control loop, and outer position control loop. Advanced algorithms such as feedforward compensation improve trajectory tracking at high speeds. Error compensation utilizes mathematical models for correction of machine geometric errors, thermal deformations, and deflections under load. Active vibration damping suppresses unwanted oscillations that would degrade machined surface quality. Multi-axis synchronization enables coordinated movement for machining complex three-dimensional surfaces.

High-speed milling places extreme demands on the mechatronic system of CNC machines. The spindle must achieve speeds of twenty thousand to sixty thousand revolutions per minute, feed rates can exceed thirty meters per minute, and axis acceleration can reach more than one g. These parameters require lightweight but rigid mechanical constructions, powerful servo drives capable of providing high accelerations, fast control loops with frequencies of several kilohertz, and sophisticated algorithms for trajectory optimization and vibration minimization.

Automated warehouses and logistics systems represent an area where mechatronics has enabled dramatic efficiency improvements. Modern automated warehouses utilize Automated Storage and Retrieval Systems that can store and retrieve pallets or smaller units with minimal human intervention.

Mechatronic aspects of AGVs include a drive system with individually controlled motors for each wheel enabling omnidirectional movement, a sensor system for navigation and obstacle detection, a control unit executing algorithms for path planning, obstacle avoidance and coordination with other vehicles, a communication system for receiving commands and reporting status, and safety systems ensuring safe operation in environments with people.

Modern warehouses can contain dozens to hundreds of AGVs coordinated by a central system that optimizes vehicle utilization and minimizes transport times. This coordination requires sophisticated algorithms for task scheduling, vehicle routing, and conflict resolution when multiple vehicles compete for the same space.

Industrial robots represent perhaps the most visible application of mechatronics in industry. MDPI Sustainability published a comprehensive article in 2024 analyzing the integration of advanced mechatronic systems into Industry 4.0 with emphasis on smart manufacturing. The article presents case studies from the automotive industry, where robots perform a wide spectrum of operations from spot and arc welding through assembly operations to material handling.

Modern industrial robots are characterized by high positioning repeatability, typically better than 0.1 millimeters, the ability to manipulate loads from several kilograms to hundreds of kilograms depending on robot type, flexibility enabling rapid reprogramming for different tasks, and integration into manufacturing cells with other automated equipment.

Mechatronic aspects of an industrial robot include mechanical construction typically with six rotational axes enabling achievement of arbitrary position and orientation in the workspace, servo drives for each axis with high power and precise control, a sensor system including encoders on each axis and optionally force-torque sensors or vision systems, a control unit executing inverse kinematics for converting desired end-effector position to individual joint angles, and trajectory planning generating smooth trajectories and communication interfaces for integration with other devices and supervisory systems.

The Industry 4.0 concept brings a new level of integration of mechatronic systems in industry. Key aspects include connectivity, where all devices are connected to the network and share data, data analytics utilizing collected data for process optimization and predictive maintenance, digital twins creating virtual replicas of physical systems, and cyber-physical systems integrating computational and physical processes.

1.3 Related Fields

Mechatronics is located at the intersection of several traditional engineering disciplines, and its understanding requires recognition of relations, overlaps, and differences from these related fields. This chapter analyzes the relation of mechatronics to mechanical engineering, electrical engineering, computer science, and robotics, and defines the specific profile of a mechatronic engineer.

Mechanical engineering provides the foundation for mechanical design and system dynamics. Mechanical engineering traditionally includes machine and mechanism design, materials engineering and selection of suitable materials, dynamics and kinematics of motion systems, thermodynamics and fluid mechanics for energy systems, and manufacturing technology and machining processes. A mechatronic engineer needs a solid foundation in these areas, but with different emphasis than a purely mechanical engineer.

In the mechatronic approach, the mechanical part is often simplified compared to purely mechanical solutions because part of the functionality is transferred to electronics and software. A mechatronic engineer must understand system dynamics well enough for designing appropriate control but does not need to be an expert in detailed mechanical design of every component. Emphasis is placed on the interaction between mechanics and control, and on how mechanical properties influence the capabilities and performance of the controlled system.

Electrical engineering and electronics provide tools for sensing, actuation, and signal processing. Electrical engineering traditionally includes circuit design of analog and digital circuits, power electronics for conversion and control of electrical energy, electrical machines and drives, signal processing and filtering, and control systems and automatic control theory. A mechatronic engineer needs understanding of these areas primarily from an application perspective.

A mechatronics engineer typically does not design circuits at the transistor level but must be able to select appropriate off-the-shelf modules, understand their specifications, and integrate them into the system. Similarly, when selecting motors and drives, it is necessary to understand their properties, control capabilities, and proper sizing, but detailed design of the motor's electromagnetic circuit is usually not required. In control systems, emphasis is on practical implementation and tuning of controllers in real applications.

Computer science and software engineering provide methods for algorithmic design and implementation. Computer science traditionally includes algorithms and data structures, programming languages and paradigms, operating systems and real-time computing, databases and information management, and artificial intelligence and machine learning. A mechatronic engineer needs the ability to program in languages relevant to embedded systems such as C, C++, or Python.

Unlike a pure software engineer, a mechatronics professional deals primarily with software closely tied to hardware and physical processes. Important is the concept of real-time execution, where software must respond to events within deterministic time limits. Timing constraints in embedded systems are often critical for proper system function.

Robotics represents one of the most visible application areas of mechatronics. Robotics integrates mechanics for construction of manipulators and motion systems, sensors for environmental perception and proprioception, actuators for motion realization, control algorithms for motion planning and execution, and AI for decision making and learning. Many academic programs include robotics as part of the mechatronic curriculum or as a separate specialization built on a mechatronic foundation.

The typical profile of a mechatronic engineer differs from the profiles of specialized engineers. A mechanical engineer has deep knowledge of mechanics, materials, and manufacturing processes but may have limited knowledge of electronics and programming. An electrical engineer has deep knowledge of circuits, power electronics, and electrical machines but may have gaps in mechanical design and software. A software engineer is an expert in algorithms, data structures, and software architecture but may have limited knowledge of hardware and physical systems

A mechatronic engineer, in contrast, has broader but less deep knowledge across all these areas. Their main value lies in the ability to integrate components from different areas into a functional whole, communicate effectively with experts from individual areas, understand interdependencies between mechanical design, electronics, and software, and make informed trade-off decisions balancing requirements from different domains.

In practice, mechatronic engineers often work as system integrators responsible for overall system architecture, or in R&D teams where an interdisciplinary perspective is needed, in product development where new products require close integration of mechanics, electronics, and software, or as technical leaders capable of coordinating the work of multi-disciplinary teams.

The trend toward interdisciplinarity in engineering is evident also in the academic sphere. Many universities have created mechatronic programs or similarly oriented interdisciplinary programs. These programs typically provide core foundation in mathematics, physics, and basic engineering subjects, balanced coverage of mechanics, electronics, and computer science, hands-on laboratory experiences with real mechatronic systems, and capstone projects requiring integration of knowledge from multiple areas.

Mechatronics thus represents not only a technical field but also a philosophy of approach to designing complex systems. It is a response to the growing complexity of modern technologies, which can no longer be effectively designed within traditional disciplinary boundaries. A successful mechatronic engineer combines technical knowledge across multiple areas with the ability to see the system as a whole and understand interactions between its parts.

2 INTRODUCTION TO CONTROL

Control represents one of the fundamental pillars of mechatronics and forms the metaphorical nervous system of every intelligent technical system. While previous chapters provided theoretical foundations in the form of systems theory, mathematical tools, and state machines, this chapter shifts focus to practical aspects of controlling mechatronic devices. Understanding control principles is essential for every mechatronic engineer, as control algorithms and systems determine how effectively and precisely a machine or process will function under real conditions.

Automatic control has undergone dramatic development since its beginnings. From simple mechanical regulators, such as Watt's centrifugal governor for steam engines from the late 18th century, to sophisticated digital control systems of today, the basic principle remains the same: measure the current state of the system, compare it with the desired state, and based on the difference generate a corrective action. This simple concept of feedback enables achievement of precision and reliability that would be unattainable with manual control.

2.1 Control – Basic Concepts

Control represents a systematic process of influencing the behavior of a dynamic system with the aim of achieving desired behavior or maintaining the system in a desired state despite the action of external disturbances. In mechatronic systems, control is a key process that integrates information from sensors, evaluates it according to a control algorithm, and generates control actions for actuators.

Control can be divided into two basic categories according to the use of information about system output. Open-loop control executes control actions without knowledge of the actual result of these actions, while closed-loop control continuously monitors system output and continuously adjusts control actions based on the difference between desired and actual values.

In control engineering terminology, specific terms have become established. The controlled variable represents the output variable of the system. The setpoint defines the target state of the controlled variable. The control error is the difference between the setpoint and actual value. The control action is the output signal from the controller. A disturbance represents an unwanted external influence.

Control quality is evaluated using criteria such as accuracy, speed, overshoot, robustness, and energy efficiency.

2.2 Open-Loop Control

Open-loop control (Fig. 2) represents the simplest approach to system control, where the control system does not use any information about the actual state of the controlled variable. The control action is determined exclusively based on the desired value and assumed process model.

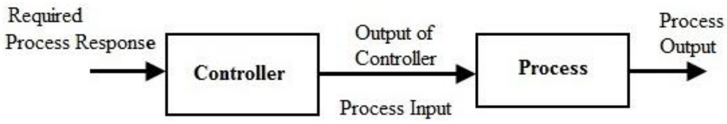

Fig. 2 Open loop control

The main advantage is structural simplicity and low cost. Disadvantages include sensitivity to disturbances, parameter changes, and limited accuracy. Practical applications include timed valve opening, heating without thermostat, and microwave oven control.

2.3 Closed-Loop Control

Closed-loop control (Fig. 3) represents a more advanced approach where the actual value is continuously measured and compared with the desired value. The controller evaluates the deviation and generates a control action to minimize it.

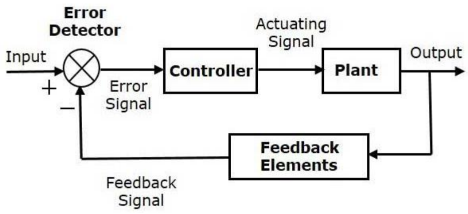

Fig. 3 Closed loop control

Advantages of closed-loop control include robustness against disturbances, automatic compensation of parameter changes, and high accuracy. Disadvantages are the need for sensors, possibility of instability, and higher complexity.
Applications dominate in the automotive industry (cruise control, ABS), industrial manufacturing (temperature regulation, position control), and energy sector (voltage regulators).

2.4 PID Controller – Basic Principle

The Proportional-Integral-Derivative (PID) controller (Fig. 4) represents the most widespread type of controller. It is estimated that 90 to 95 percent of all industrial control loops utilize PID controllers.

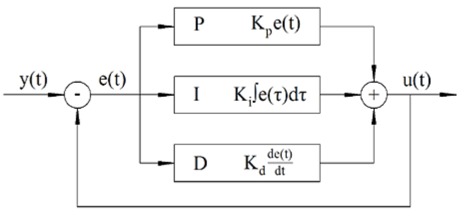

Fig. 4 PID regulation

The PID controller combines three basic control actions. Mathematical description in continuous time:

$$u(t) = K_p e(t) + K_i \int e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

Alternative form with integral and derivative time:

$$u(t) = K_p \left[e(t) + \frac{1}{T_i} \int e(\tau)d\tau + T_d \frac{de(t)}{dt} \right]$$

In transfer function:

$$G(s) = K_p \left(1 + \frac{1}{T_i s} + T_d s \right)$$

Proper parameter setting is critical for system performance. The process of finding optimal parameters is called controller tuning.

2.5 Proportional Component

The proportional component (P-component) is the most basic type of action, where the control action is directly proportional to the deviation:

$$u_p(t) = K_p e(t)$$

A proportional controller reacts immediately to a change in deviation. A critical limiting factor is the existence of steady-state error:

$$e_{ss} = \frac{1}{1 + K_p G(0)}$$

The choice of K_p requires a compromise between speed of response and stability. Higher K_p means faster response, but the risk of oscillations increases.

2.6 Integral Component

The integral component (I-component) is added to eliminate steady-state error:

$$u_i(t) = K_i \int e(\tau)d\tau = \frac{K_p}{T_i} \int e(\tau)d\tau$$

The integral action accumulates the history of deviations. A short integral time means strong action, a long time means slow action.

In practice, a PI controller (Fig. 5) (without derivative component) is often used, which provides an excellent compromise between speed and accuracy.

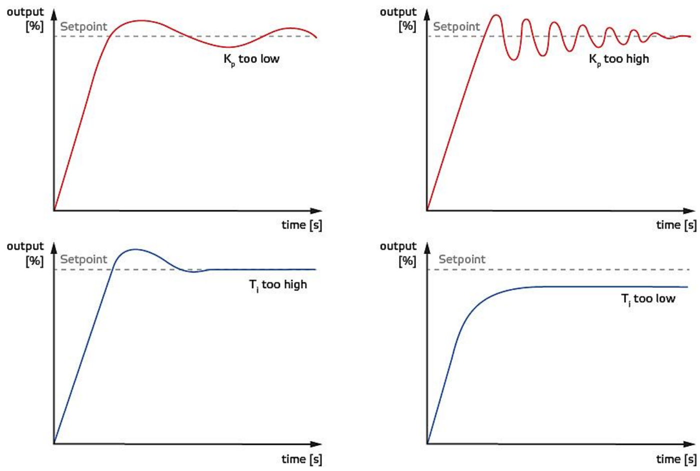

Fig. 5 PI regulation

A significant problem is integral windup – saturation of the integrator when the actuator saturates. The solution is anti-windup mechanisms (Fig. 6).

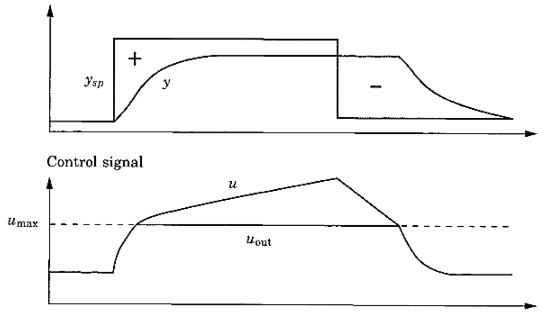

Fig. 6 Integral windup

2.7 Derivative Component

The derivative component (D-component) generates a control action proportional to the rate of change of deviation:

$$u_d(t) = K_d \frac{de(t)}{dt} = K_p T_d \frac{de(t)}{dt}$$

The derivative has predictive and damping character – it reacts to the rate of change, not to the magnitude of deviation. Advantages include improved stability and reduced overshoot.

A critical disadvantage is sensitivity to noise. The solution is filtered derivative:

$$G_d(s) = \frac{K_p T_d s}{1 + \frac{T_d s}{N}}$$

Typical values of N are 8 to 20. The derivative component is added only in cases where the process is slow or has a tendency to oscillate.

2.8 PID Controller Tuning

Tuning represents the process of finding optimal values of parameters K_p, K_i, and K_d (Fig. 7).

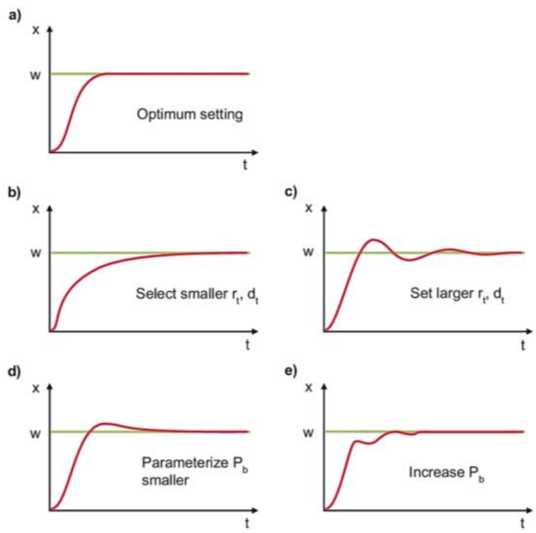

Fig. 7 PID regulator tuning

Tuning methods include empirical (trial-and-error), analytical (requiring a model), heuristic, and adaptive methods.
The most famous is the Ziegler-Nichols method in two variants:
1. Critical gain method – increasing K_p until sustained oscillations
2. Step response method – analysis of process response in open loop
For PID controller using critical gain method:

$$K_p = 0.6 \cdot Kcr, T_i = 0.5 \cdot Tcr, Td = 0.125 \cdot Tcr$$

Modern PLCs contain an autotuning function that automatically identifies the process and tunes the controller.

2.9 PLC – Basics

The Programmable Logic Controller (PLC) is a specialized industrial computer designed for controlling machines under demanding conditions. The first PLC, MODICON 084, was introduced in 1969.
Basic PLC architecture consists of a CPU (executes the program), memory (stores program and data), input-output modules (interface to sensors and actuators), power supply module, and communication interfaces (Fig. 8).

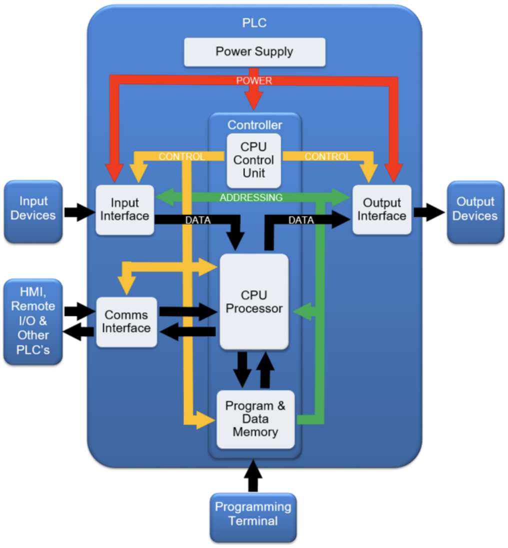

Fig. 8 PLC structure

Advantages of PLCs include programmability, compactness, modularity, reliability, and diagnostic capabilities. Programming is standardized by the IEC 61131-3 standard, which defines five languages:
- Ladder Diagram (LD) – graphical language for sequential control
- Function Block Diagram (FBD) – blocks for continuous regulation
- Sequential Function Chart (SFC) – for sequential processes
- Structured Text (ST) – text language for complex algorithms
- Instruction List (IL) – low-level language

2.10 PLC Applications

PLCs are an integral part of modern industrial automation. In the automotive industry, they control assembly lines, welding, painting, and robots. In manufacturing automation, they are the heart of CNC machines, automated warehouses, and packaging systems.

In the food and pharmaceutical industries, they control dosing, mixing, filling, and sterilization while maintaining hygienic standards. In the energy sector, they control pumping stations, wastewater treatment plants, and HVAC systems.

PLCs can operate standalone or in hierarchical structures with SCADA systems and MES/ERP systems. Modern PLCs support motion control, PID regulation, and advanced communication protocols.

PLC operation represents a key skill for mechatronic engineers and is highly valued in the job market.

3 SENSORS

Sensors represent the sensory organs of mechatronic systems, mediating information about the state of the physical world to the control system. Without reliable and accurate sensors, it is impossible to implement a closed-loop control system or achieve the required quality of control for automated systems. In modern mechatronic applications, we encounter dozens of sensor types measuring a wide spectrum of physical quantities from mechanical parameters such as position, velocity, and acceleration, through thermal quantities such as temperature, to pressures in pneumatic and hydraulic systems.

The quality of the entire mechatronic system is largely limited by the quality of the sensors used. Even if we have a powerful actuator and sophisticated control algorithm, insufficient accuracy or slow sensor response can significantly limit the resulting system properties. When designing a mechatronic system, it is therefore essential to pay sufficient attention to the selection of appropriate sensors, taking into account application requirements, operating conditions, and available budget.

3.1 Role of Sensors in Mechatronics

Sensors in mechatronics fulfill several basic functions. The primary task is to measure a physical quantity and convert it to an electrical signal that can subsequently be processed in the control system. In closed-loop control systems, sensors provide feedback about the actual state of the system, enabling comparison with the desired state and calculation of the control action. In diagnostic applications, sensors monitor the operation of devices and enable early detection of faults or anomalies.

The development of sensor technologies in recent decades has brought significant progress in miniaturization, accuracy, and integration. Microelectromechanical systems known as MEMS have enabled the creation of miniature sensors with excellent parameters at an acceptable price. Integration of sensors with processing electronics on a single chip leads to intelligent sensors that provide digital output with automatic error compensation and diagnostic functions.

3.2 Basic Sensor Characteristics

Each sensor is characterized by a set of parameters defining its properties and applicability in a specific application. Understanding these characteristics is key to proper sensor selection and interpretation of measured values. The measurement range determines the minimum and maximum values of the measured quantity within which the sensor can operate. Exceeding the maximum value can lead to permanent sensor damage, while measuring values close to the lower limit of the range often means lower accuracy.

Sensor accuracy expresses the maximum deviation of the measured value from the true value of the measured quantity. Accuracy is usually stated as a percentage of full scale or as an absolute value in units of the measured quantity. It is necessary to distinguish between accuracy and repeatability, where repeatability indicates the extent to which the sensor provides the same value when repeatedly measuring the

same quantity under the same conditions. A sensor can have good repeatability but poor accuracy due to systematic error, which can often be removed by calibration.
Sensor resolution indicates the smallest detectable change in the measured quantity. For digital sensors, resolution is determined by the number of bits of the analog-to-digital converter; for example, a twelve-bit converter has a resolution of one in 4096 steps in the given range. Response speed or frequency characteristic determines how quickly the sensor reacts to a change in the measured quantity. The sensor time constant is the time required to reach 63.2 percent of the final value with a step change in the measured quantity.
Linearity of the characteristic indicates the extent to which the sensor output signal depends linearly on the measured quantity. An ideal sensor has a perfectly linear characteristic; real sensors exhibit certain nonlinearity, which is expressed as the maximum deviation from the ideal straight line. Hysteresis is the difference in output signal at the same value of the measured quantity depending on whether this value was approached from lower or higher values. Sensor drift denotes a slow change in the output signal at constant measured quantity, which may be caused by component aging or temperature changes.

3.3 Analog vs. Digital Sensors

Analog sensors provide output in the form of a continuous electrical signal, most commonly voltage or current, which is proportional to the measured quantity. A typical analog sensor can generate voltage in the range of zero to ten volts or a current loop of four to twenty milliamps. The advantage of analog sensors is simplicity of construction, direct proportionality between the measured quantity and output signal, and the possibility to implement high sampling frequencies with external signal processing. The disadvantage is sensitivity to electromagnetic interference, the need for quality cable shielding for transmission over greater distances, and the necessity of analog-to-digital conversion for digital processing in microcontrollers.
For transmitting analog signals over distance, a four to twenty milliamp current loop is preferred over voltage signal. Current is not affected by line resistance as voltage is, which ensures accurate information transmission even over hundreds of meters. The lower limit of four milliamps allows distinguishing zero measurement from line break. Voltage signals are suitable for short distances up to several meters, where quality shielding can be ensured and the influence of interference minimized.
Digital sensors have a built-in analog-to-digital converter and provide direct numerical output, often via standard communication buses such as I^2C, SPI, CAN, or RS-485. Modern industrial networks such as Profibus, DeviceNet, or EtherCAT enable connection of a large number of sensors to a single bus. Digital sensors are resistant to interference during transmission, as small signal changes do not affect numerical values. They enable data transmission over arbitrary distances without loss of accuracy and can contain extensive diagnostics and error compensation directly in their firmware.

The disadvantage of digital sensors is higher cost and electronics complexity compared to analog variants. The output signal is discrete in time due to sampling and in amplitude due to quantization, which can be disadvantageous in applications requiring very high sampling frequencies. However, modern systems prefer digital sensors due to their advantages in interference resistance, easier integration into control systems, and possibility of remote diagnostics and parameterization.

3.4 Temperature Sensors – Thermocouples

Thermocouples are among the most widespread temperature sensors utilizing the thermoelectric effect discovered by Thomas Seebeck in 1821. The operating principle is that when two different metals are joined, a temperature-dependent voltage arises at their contact. When two junctions of different metals are maintained at different temperatures, a thermoelectric voltage proportional to the temperature difference is created between them. By measuring this voltage and knowing the temperature of the reference junction, the temperature of the measuring junction can be determined.

Different metal combinations provide different thermocouple properties, which are standardized and designated by letter. The most commonly used types include Type K with chromel-alumel conductors with a range of minus two hundred to plus one thousand two hundred fifty degrees Celsius, Type J with an iron-constantan combination for a range of minus two hundred to plus seven hundred fifty degrees Celsius, and Type T with a copper-constantan combination suitable for lower temperatures from minus two hundred seventy to plus four hundred degrees Celsius. For high-temperature applications, Type S with platinum-rhodium conductors working up to one 1700 degrees Celsius is used.

(example of thermocouple designation and parameters)

The advantage of thermocouples is low cost, robustness, ability to measure a very wide temperature range, and possibility to create a measurement point of very small dimensions with fast response. Thermocouples do not require external power and generate their own voltage, which is advantageous in explosive atmospheres. Disadvantages include low output voltage on the order of millivolts to microvolts, requiring precision amplifiers and quality shielding. Characteristic nonlinearity requires the use of conversion tables or polynomial approximations. A key problem when working with thermocouples is reference junction compensation. Since the temperature difference between the measuring and reference junctions is measured, the temperature of the reference junction must be known, which is usually located in the evaluation electronics. For cold junction compensation, an auxiliary temperature sensor is used that measures the reference junction temperature and this value is added to the measured thermoelectric value. Modern integrated circuits for thermocouple signal processing have built-in automatic cold junction compensation.

3.5 Temperature Sensors – Resistance (RTD)

Resistance temperature sensors designated as RTD come from the English Resistance Temperature Detector and utilize the property of pure metals to change their electrical resistance depending on temperature. The physical principle is that with increasing temperature, the amplitude of thermal vibrations of the crystal lattice atoms increases, which increases the probability of scattering of moving electrons and thus the electrical resistance of the material. The resistance change with temperature in pure metals is practically linear over a wide temperature range and well reproducible (Fig. 9).

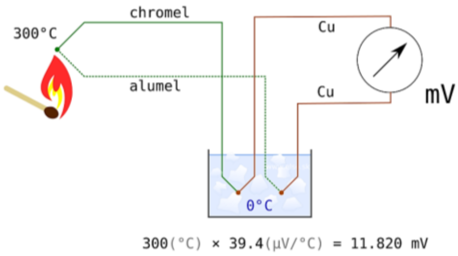

Fig. 9 The principle of operation of a thermocouple

The most commonly used material for RTD is platinum due to its high chemical stability, resistance to oxidation, and excellent characteristic linearity. The standard Pt100 sensor has a resistance of exactly one hundred ohms at zero degrees Celsius and a temperature coefficient of resistance of 0,385 ohms per ohm per degree Celsius according to European standard IEC 60751. This coefficient means that with a temperature increase of one hundred degrees Celsius, the resistance increases by approximately 38,5 ohms. In addition to Pt100, variants Pt500 and Pt1000 with higher nominal resistance values are also manufactured, providing higher output signal.

RTD sensors (Fig. 10) are significantly more accurate than thermocouples, typically with an accuracy of 0,1 to 0,5 degrees Celsius in the range of minus two hundred to plus six hundred fifty degrees Celsius for Pt100.

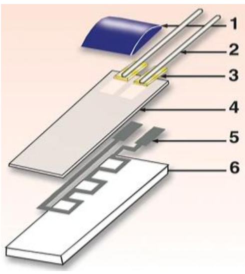

Fig. 10 Resistance sensor design
1 – junction protection, 2 – connecting line, 3 – connecting pads, 4 – glass coating, 5 – platinum element, 6 - ceramic

The characteristic is substantially more linear than thermocouples, simplifying signal processing. RTD are stable over long periods and do not require frequent calibration. The disadvantage is higher cost than thermocouples and lower maximum operating

temperature. RTD also have slower response than thermocouples due to larger thermal mass.
Measuring RTD resistance requires a current source and precise voltmeter. The problem is that current flowing through the sensor causes self-heating according to Joule's law P equals I squared R, which distorts measurement. Therefore, low measuring currents on the order of one to five milliamps are used. For precise measurements, a four-wire connection is used eliminating the influence of lead resistance. Current is fed through one pair of conductors and voltage is measured by another pair with high input resistance, so lead resistance does not affect measurement
Structurally, RTDs are made as thin-film or wire sensors. Thin-film sensors are made by sputtering a thin film of platinum onto a ceramic substrate, which allows for miniaturization and mass production at an affordable price. Wire RTDs contain a precisely wound platinum wire. Measurements are made using compensated evaluation cards.
The accuracy of RTD measurements is affected by the resistance of the lead wires, which in a two-wire connection is added to the resistance of the sensor itself and causes measurement errors. This problem is solved by a three-wire connection, where two wires connect one end of the sensor and a third wire the other end (Fig. 11).

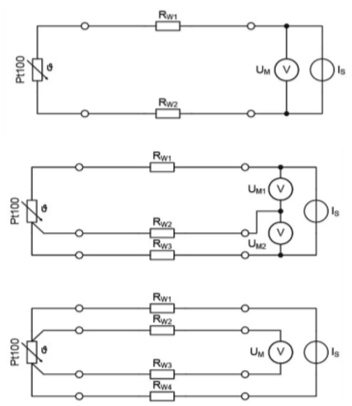

Fig. 11 Comparison of two-wire, three-wire and four-wire RTD connections

When measuring with a bridge, the resistance of the lead wires is compensated. The more simple four-wire connection completely eliminates the influence of the wires by using two wires to supply the measuring current and two wires to measure the voltage without flowing current.

3.6 Temperature Sensors – Thermistors

Thermistors are semiconductor temperature sensors utilizing the strong temperature dependence of semiconductor material resistance. Unlike RTD where resistance increases with temperature, most thermistors are NTC type (Negative Temperature Coefficient) with resistance decreasing with increasing temperature. There are also PTC thermistors (Positive Temperature Coefficient) with increasing resistance, but these are less common for temperature measurement.

NTC thermistors have very high sensitivity, typically several percent change in resistance per degree Celsius. This provides much higher signal than RTD or thermocouples, simplifying signal processing electronics. Thermistors are cheap to manufacture and available in very small sizes enabling fast thermal response. The disadvantage is strong nonlinearity of the characteristic and limited temperature range, typically -50 to plus 150 degrees Celsius, although specialized types can work to 300 degrees Celsius.

The resistance-temperature relation of an NTC thermistor is described by the Steinhart-Hart equation, which is a third-order polynomial approximation. For practical applications, the simplified beta equation is often used, where R(T) is resistance at temperature T, R0 is resistance at reference temperature T0, beta is a material constant, and temperatures are in Kelvins. The beta coefficient is typically in the range of 3000-5000 Kelvins.

Thermistor calibration requires measuring resistance at several known temperatures and fitting equation parameters. For accurate measurements, the Steinhart-Hart equation with three parameters provides better accuracy than the simpler beta equation. Some manufacturers provide calibration coefficients for individual thermistors, enabling accuracy of hundredths of a degree Celsius.

Applications of thermistors include temperature monitoring of electronics, compensation of temperature influences in circuits, and household temperature measurement in thermostats and air conditioners. In mechatronics, thermistors are used for motor temperature monitoring, battery temperature measurement in electric vehicles, and protection against overheating of power electronics.

3.7 Temperature Sensors – Infrared (Pyrometers)

Infrared temperature sensors, called pyrometers, measure temperature contactlessly based on thermal radiation emitted by objects. Every object with temperature above absolute zero emits electromagnetic radiation in the infrared range. The intensity and wavelength spectrum of this radiation depends on object temperature according to Planck's law and Stefan-Boltzmann law.

Pyrometers measure the intensity of infrared radiation and from it determine object temperature. The advantage of contactless measurement is the ability to measure moving objects, objects at very high temperatures that would damage contact sensors, and measurements in aggressive environments. Pyrometers enable fast response as they are not limited by thermal mass of the sensor. The disadvantage is that measurement is affected by object emissivity, which depends on material and surface finish. Shiny metallic surfaces have low emissivity and reflect surrounding radiation, complicating accurate measurement.

Emissivity epsilon is a coefficient from zero to one indicating how effectively an object emits thermal radiation compared to an ideal black body. For accurate measurement, emissivity must be known or set in the pyrometer. Matte, dark surfaces have high emissivity close to 0.9, while polished metals can have emissivity below 0,1. Many pyrometers allow emissivity adjustment or have presets for common materials.

Pyrometers are divided into single-wavelength and two-wavelength (ratio) types. Single-wavelength pyrometers measure radiation intensity at one wavelength and from it determine temperature. Two-wavelength pyrometers measure radiation at two different wavelengths and calculate temperature from their ratio. Ratio pyrometers are less sensitive to emissivity changes and partial obscuration of the optical path.
Applications of pyrometers include monitoring temperatures in metallurgy and glassmaking, where materials reach thousands of degrees Celsius. In the automotive industry, they monitor tire temperatures during testing. In electronics manufacturing, they control soldering temperature in reflow ovens. In diagnostics, they detect overheating of electrical connections and components. Thermal cameras represent an extension of pyrometers measuring temperatures across the entire scene and creating thermal images.

3.8 Pressure Sensors – Basic Principles

Pressure sensors are a key group of sensors in mechatronic systems, as they allow monitoring and control of pneumatic and hydraulic drives, processes in the chemical industry and engine control. The physical principle of pressure measurement consists in converting the mechanical deformation of a membrane or other elastic element caused by pressure into an electrical signal. This conversion is carried out by various physical principles, the most widespread of which are the piezoresistive effect, the capacitive change and the piezoelectric effect.
When measuring pressure, it is necessary to specify the reference pressure against which the measurement is made. Absolute pressure is measured against a perfect vacuum, i.e. against zero pressure. Absolute pressure is important in applications where it is necessary to know the actual pressure value independent of changes in atmospheric pressure, such as in barometers or in internal combustion engine control systems. Relative or manometric pressure is measured against atmospheric pressure and is most often used in industry. Pneumatic systems typically operate with a relative pressure of 6 bar.
Differential pressure represents the difference between two pressures and is used to measure flow through screens, monitor filter clogging or control ventilation in clean rooms. A differential pressure sensor has two pressure connections and measures the pressure difference between them. The measuring range of pressure sensors is extremely wide, from a few pascals when measuring vacuum in HVAC systems to hundreds of megapascals in hydraulic presses. It is necessary to select a sensor with the appropriate range for each application, as an oversized range leads to poor accuracy when measuring low pressures and an undersized range to the risk of damage due to switching.
The diaphragm material and design of the pressure sensor are selected according to the measured medium and the operating conditions. For aggressive chemicals, diaphragms made of stainless steel, tantalum or ceramic are used. When measuring viscous media, sensors with direct contact of the diaphragm with the medium are

applied, while for clean gases, more compact designs are sufficient. The thermal stability of the sensor is also important, because temperature affects the properties of materials and can cause measurement errors, which is why quality sensors include thermal compensation.

3.9 Strain gauge pressure sensors – tensometers

Strain gauge pressure sensors are the most widely used type of industrial pressure sensor due to their excellent combination of accuracy, stability and price. The operating principle is based on the piezoresistive effect, which is characterized by a change in the electrical resistance of a material under mechanical stress. When a force is applied to the material causing it to deform, not only its geometry but also its specific electrical resistance changes, leading to an overall change in the resistance of the conductive element.

A strain gauge pressure sensor consists of a thin flexible membrane onto which a set of resistors arranged in a Wheatson bridge is soldered or diffused. When pressure is applied to the membrane, it deforms and induces a stress in the material. The resistors located along the radial stress decrease, while the resistors located along the tangential stress increase. This arrangement in the Wheatson bridge maximizes sensitivity and at the same time compensates for the effect of temperature, since temperature changes affect all resistors equally.

Silicon piezoresistive sensors use monocrystalline silicon, into which regions with a very high piezoresistive coefficient are diffused, many times higher than those of metal strain gauges. Micromechanical processing allows the creation of very thin membranes with high sensitivity and small dimensions. These MEMS sensors are manufactured in thousands on a single silicon wafer, which significantly reduces production costs. Integration with electronics on the same chip allows amplification, compensation and digital output to be implemented in one compact package. The advantages of strain gauge pressure sensors (Fig. 12) include high accuracy typically from 0,1 to 0,25 percent of full scale, a wide range of measurement ranges from kilopascals to hundreds of megapascals, good linearity of the characteristic and the ability to measure both static and dynamic pressures. Stability over time is excellent due to the absence of moving parts. Disadvantages include temperature sensitivity requiring compensation, the possibility of damage from switching, and a relatively higher price compared to simple mechanical pressure gauges, although MEMS technology has significantly reduced this price.

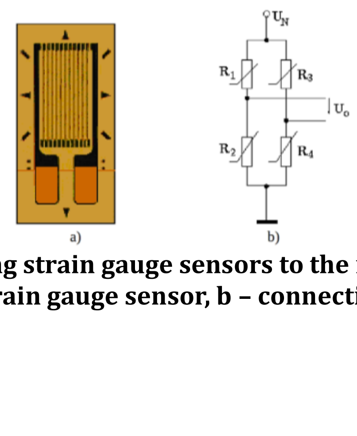

Fig. 12 Connecting strain gauge sensors to the measuring bridge
a – appearance of the strain gauge sensor, b – connecting the measuring bridge

3.10 Pressure Sensors – Capacitive

Capacitive pressure sensors measure pressure change as a capacitance change between two electrodes. One electrode is on a flexible membrane deflecting under pressure, the second electrode is fixed. Deflection changes the gap between electrodes and thus capacitance. Capacitive sensors have excellent sensitivity and stability. They can measure very low pressures down to pascals and very high pressures to hundreds of megapascals with a single design. Linearity and repeatability are very good. The disadvantage is sensitivity to temperature changes and parasitic capacitances in leads, requiring careful circuit design (Tab. 1).

Tab. 1 Comparison of pressure sensor technologies Technology

Technology	Operating principle	Advantages	Disadvantages	Typical applications
Piezoresistive	Measures the change in electrical resistance of a material (often silicon or ceramic) due to mechanical stress caused by pressure.	High accuracy and stability, good linearity, relatively low price, wide availability.	Sensitivity to temperature changes (requires temperature compensation), may be affected by electromagnetic interference.	Automotive industry (TPMS, engine management), medical devices (blood pressure monitors), industrial automation, HVAC systems.
Capacitive	Measures the change in capacitance between two parallel plates, one of which is a flexible membrane that deforms under pressure.	High sensitivity, low temperature drift, low power consumption, excellent long-term stability.	More complex design and calibration, more susceptible to impurities and moisture in the measured medium, potentially higher manufacturing costs.	Barometric pressure sensors, weather stations, altitude measurement, industrial process control.
Piezoelectric	Uses the piezoelectric phenomenon, in which some materials generate an electrical charge when exposed to pressure or mechanical stress.	Very fast response, ideal for measuring dynamic pressures and shocks.	Not suitable for measuring static pressure (generates charge only when pressure changes), requires special electronics for signal processing.	Explosion measurement, engine testing, dynamic analyses in industry, ultrasonic applications.
Optical (fiber optic)	Measures the change in light transmission, wavelength, or phase shift in optical fiber that occurs due to pressure acting on the sensing element.	Immunity to electromagnetic interference, possibility of use in hazardous (explosive) environments, high accuracy over long distances.	Higher price, more complex installation and measuring equipment, sensitivity of optical fiber to damage.	Oil and gas industry (drilling, pipelines), medical applications (invasive measurements) structural monitoring.
Resonant	Measures the change in resonant frequency of a mechanical element that changes under the influence of applied pressure.	Extremely high long-term stability, very high accuracy, self-calibration.	Higher complexity and price compared to common types.	Reference and calibration standards, precise industrial processes, meteorology, aviation.

Differential capacitive sensors use two capacitors with a common movable electrode on the membrane. When pressure increases, one capacitance increases and the other decreases. Measurement of the capacitance difference provides higher sensitivity and better temperature compensation. Applications include barometers for atmospheric pressure measurement, altitude sensors in aircraft and drones, precise laboratory instruments, and consumer electronics such as smartphones where they measure altitude and weather changes

3.11 Pressure Sensors – Piezoelectric

Piezoelectric pressure sensors use the property of certain crystals to generate electric charge when mechanically stressed. Quartz and some ceramics such as PZT (lead zirconate titanate) are used. A piezoelectric element loaded by pressure generates charge proportional to force. The advantage of piezoelectric sensors is extremely fast response, enabling measurement of dynamic pressure changes up to frequencies of hundreds of kilohertz. They have very high stiffness and do not require external power for measurement. The disadvantage is that they cannot measure static pressure; they only respond to pressure changes. Charge gradually leaks, so the signal decays with a time constant depending on input impedance of the measuring circuit.

Piezoelectric sensors require charge amplifiers with very high input impedance or integrated MOSFET circuits for impedance conversion. Modern sensors have integrated electronics providing voltage or current output.

Applications include measurement of combustion pressure in internal combustion engines, monitoring of dynamic pressures in hydraulics and pneumatics, measurement of impact and blast forces, and ultrasonic applications. In automotive industry, they monitor injection and combustion in engines for diagnostics and optimization.

3.12 Position Sensors – Potentiometers

Potentiometers are among the simplest position sensors based on resistive divider principle. Potentiometer consists of a resistive element with total resistance R and a movable contact (wiper) that divides the resistance into two parts. When voltage U is applied across the entire resistive element, voltage at the wiper position is proportional to wiper position.

Rotary potentiometers measure angular position and are available in single-turn variants for angles up to 360° and multi-turn variants for multiple rotations, typically three to ten turns. Linear potentiometers measure linear position and are manufactured in lengths from millimeters to meters.

The advantage of potentiometers is simplicity, low cost, and direct analog output requiring minimal signal processing. The disadvantage is mechanical wear of the wiper contact, limiting lifespan to millions of cycles. Oxidation and contamination of the resistive element can cause noise and nonlinearities. Potentiometers are also sensitive to vibrations that can cause intermittent contact.

Quality potentiometers use conductive plastic resistive elements providing better wear resistance than wire-wound variants. For industrial applications, contactless position sensors are preferred despite higher cost due to longer lifespan and higher reliability.

3.13 Position Sensors – LVDT

Linear Variable Differential Transformer (LVDT) is a contactless linear position sensor based on the principle of electromagnetic induction. LVDT consists of a primary coil and two secondary coils symmetrically arranged around a movable ferromagnetic core. The primary coil is energized with AC voltage of several kilohertz. When the core is in the center position, voltages induced in both secondary coils are equal and when connected in differential connection (series opposition), the total output voltage is zero.

When the core moves from the center position, the coupling between the primary coil and one secondary increases while the coupling with the second secondary decreases. This creates a differential output voltage whose amplitude is proportional to core displacement and whose phase indicates displacement direction. Electronics for signal processing typically includes demodulation of the AC signal and conversion to DC voltage proportional to position.

The advantage of LVDT is contactless principle ensuring unlimited lifespan, high linearity typically better than 0.5 % over the measuring range, and high resolution limited only by signal processing electronics. LVDT are robust and resistant to harsh environments including high temperatures, vibrations, and contamination. They operate reliably in radiation fields and vacuum.

The disadvantage is relatively large dimensions and weight compared to modern electronic sensors. LVDT require signal processing electronics for excitation and demodulation, which increases cost. Sensitivity to external magnetic fields can cause errors if not properly shielded. Measuring range is typically from millimeters to tens of centimeters, although special types can measure over a meter.

LVDT applications include precise position measurement in hydraulic and pneumatic actuators, monitoring of valve positions, measurement of small deformations in material testing, and calibration standards in metrology laboratories. In aerospace, LVDT are used for measuring control surface positions and landing gear extension due to their high reliability.

3.14 Position Sensors – Encoders

Encoders are digital position sensors providing output in the form of pulse sequences or binary codes. They are divided into incremental and absolute encoders. Incremental encoders generate a pulse train where each pulse corresponds to a defined position increment. By counting pulses, the controller determines the distance traveled from a reference point. Absolute encoders provide a unique code for each position within the measuring range (Fig. 13).

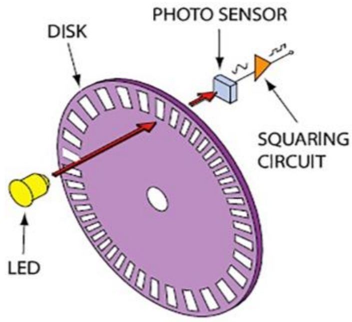

Fig. 13 Optical encoder principle

Incremental rotary encoders consist of a disc with alternating transparent and opaque segments. An infrared LED and photodetector are placed on either side of the disc. As the disc rotates, the photodetector registers a sequence of light and dark areas generating a square wave signal. The number of pulses per revolution defines encoder resolution, with common values from one hundred to ten thousand pulses per revolution.
(principle of operation)
Quality incremental encoders have two output channels A and B phase-shifted by ninety degrees, enabling detection of rotation direction and quadrature decoding. By detecting rising and falling edges on both channels, resolution increases four times. Some encoders have a third channel Z generating one pulse per revolution, serving as a zero mark for position reference.
(incremental vs. absolute encoder)
The measurement resolution can be increased by using quadrature decoding, where not only the leading edges of signal A but also the leading and trailing edges of both signals A and B are evaluated. This X4 mode provides four pulses per original encoder segment, which increases the resolution fourfold. For example, an encoder with a thousand segments provides four thousand increments per revolution in X4 mode. A further increase in resolution is achieved by interpolation of sinusoidal signals, where analog waveforms and their ratio are used instead of digital edges. Most incremental encoders also provide an index signal Z, which generates one pulse per revolution at a precisely defined position. The index pulse is used to initialize a counter, verify the number of pulses, or synchronize with other processes. In linear encoders, multiple reference marks can be spaced along the scale at precise distances.
The advantages of incremental encoders include high resolution, a non-contact measurement principle ensuring a long service life, resistance to vibration and shock, fast response enabling high speed measurement and relatively low cost compared to absolute encoders.
The disadvantages are the loss of position information when the power is turned off, as the encoder only provides a relative change in position. After the system is turned on, a reference run to a known position is required to initialize the counter. Another problem is the possibility of losing pulses at very high speeds or when the signal is interrupted, which leads to the accumulation of position error. Therefore, incremental

encoders are suitable for closed control loops, where the position is constantly updated and any errors are compensated for by feedback.
Absolute encoders are an advanced category of position sensors that provide direct position information without the need for pulse counting or referencing a home position. Unlike incremental encoders, which were discussed in the previous chapter, absolute encoders remember the position even after power is turned off, which is their most significant advantage.
The principle of operation of absolute encoders is to encode each position with a unique binary or Gray code. The encoding scale contains multiple tracks that are illuminated by a light source and read by a system of photodetectors. Each track represents one bit of digital information, with the number of tracks determining the encoder resolution. For example, an encoder with ten tracks can distinguish 1024 different positions per revolution, which corresponds to an angular resolution of approximately 0,35°.
(principle of operation)
Absolute encoders provide a unique binary or Gray code for each position. When power is restored, the controller immediately knows position without the need for homing. Single-turn absolute encoders cover positions within one revolution, multi-turn encoders remember positions over multiple rotations using mechanical gearing or battery backup.
Absolute encoders use various coding discs with binary or Gray code tracks. Gray code is preferred because it changes only one bit between adjacent positions, minimizing errors during transitions. Common resolutions are twelve to sixteen bits for single-turn encoders, providing forty-ninety-six to sixty-five thousand five hundred thirty-six unique positions per revolution.
Using Gray code instead of conventional binary code is common practice for absolute encoders. Gray code has the property that adjacent values differ by only one bit, which significantly reduces the probability of erroneous readings when switching between positions. With a classic binary code, for example, switching from value 15 (1111) to value 16 (10000) would require a simultaneous change of all bits, which can lead to transient errors. Gray code eliminates this problem.
The resolution of absolute encoders is typically in the range of 8 to 16 bits, which corresponds to 256 to 65536 positions per revolution. For applications requiring even higher resolution, there are also multiturn encoders that can distinguish not only the position within one revolution, but also the total number of revolutions. These encoders use additional gears and encoder discs, allowing position measurement over multiple complete revolutions.
The main difference between binary and Gray codes is the nature of the transitions between adjacent numbers. Binary code is a weighted code (each bit has its own numerical weight), while Gray code is unweighted and cyclic.
Key differences:
Hamming distance (number of bits changed): When changing from one decimal number to the next, only one bit changes in Gray code (Hamming distance is 1). In

binary code, all four bits change in some transitions (for example, from 7 (0111) to 8 (1000)), which can lead to transition errors (so-called glitches).

Applications:

Binary code is used in digital computer systems for arithmetic operations because it is weighted and easy to calculate.

Gray code is primarily used in devices that sense position (e.g., rotary position sensors), where it is important to minimize transition errors when changing values, because changing only one bit provides a smoother and more reliable transition.

Conversion: Conversion between binary and Gray code is simple and uses an exclusive OR (XOR) operation.

Tab. 2 Comparison of binary and Gray code for 4-bit encoding

Decimal number	Binary Coded Decimal (BCD)	Gray code	Number of bits changed (go to next number)
0	0000	0000	1 (0 na 1)
1	0001	0001	1 (0 na 1)
2	0010	0011	1 (1 na 0)
3	0011	0010	1 (1 na 0)
4	0100	0110	1 (0 na 1)
5	0101	0111	1 (0 na 1)
6	0110	0101	1 (1 na 0)
7	0111	0100	1 (1 na 0)
8	1000	1100	1 (0 na 1)
9	1001	1101	1 (0 na 1)
10	1010	1111	1 (1 na 0)
11	1011	1110	1 (1 na 0)
12	1100	1010	1 (0 na 1)
13	1101	1011	1 (0 na 1)
14	1110	1001	1 (1 na 0)
15	1111	1000	1 (1 na 0)

Optical encoders are the most common type, but there are also magnetic encoders using magnetoresistive or Hall sensors reading a magnetic pattern on a rotating disc. Magnetic encoders are more resistant to contamination and vibrations but typically have lower resolution than optical ones.

Absolute encoder communication interfaces include parallel communication, where each bit is transmitted on a separate wire, or serial communication via protocols such as SSI (Synchronous Serial Interface), BiSS, EnDat or Ethernet-based protocols. Serial communication is preferred in modern applications due to the smaller number of wires, greater immunity to interference and the ability to transmit diagnostic information.

In mechatronic systems, absolute encoders are used wherever it is critical to know the exact position even after a power failure. Typical applications include robotic arms, where each joint needs to know its position when the system is turned on, precise

positioning tables in the machine tool industry, automatic gates and doors, as well as the control of hydraulic or pneumatic cylinders where precise position feedback is required. The advantage over incremental encoders is that the need for referencing is eliminated, which speeds up system initialization and increases its robustness.
(absolute encoder)
Applications of encoders include motor position and speed control in servo systems, robotics for monitoring joint positions, machine tools for precise positioning of tools, and conveyor systems for synchronization and position tracking

3.15 Position Sensors – Linear Scales

Linear scales are sensors for measuring linear position in machine tools, coordinate measuring machines, and precision positioning systems. Linear scales operate on similar principles as rotary encoders but measure linear displacement instead of angular position.
Incremental linear scales have a measurement bar with periodically arranged marks. The reading head scans these marks and generates pulse signals. Resolution is determined by the period of the marks, typically from one to twenty micrometers. Using interpolation, resolution can be increased ten to one hundred times.
Absolute linear scales have a coded pattern along the entire length enabling unique position identification. Measuring lengths range from tens of millimeters to tens of meters with resolution from fractions of micrometers to millimeters depending on application.
Linear scales are manufactured in optical, magnetic, and capacitive variants. Optical scales provide the highest resolution and accuracy but require protection against contamination. Magnetic scales are more robust and resistant to dust and liquids but have lower resolution. Capacitive scales offer good compromise between resolution and robustness.
Important parameters of linear scales are accuracy, repeatability, and temperature stability. Quality scales have accuracy better than a few micrometers per meter of length. Temperature compensation is important as thermal expansion of the scale and measured machine affects measurement. Some scales have integrated temperature sensors for automatic compensation.
Applications include CNC machine tools for precise positioning of axes, coordinate measuring machines in quality control, semiconductor manufacturing for wafer positioning, and optical assembly requiring positioning with micrometer accuracy.

3.16 Proximity Sensors – Inductive

Inductive proximity sensors (Fig. 14) detect the presence of metallic objects contactlessly at short distances. The principle is based on generating a high-frequency alternating magnetic field by a coil in the sensor. When a metallic object enters this field, eddy currents are induced in it, which load the oscillator and change its amplitude or frequency. Signal processing electronics detect this change and activate the output.

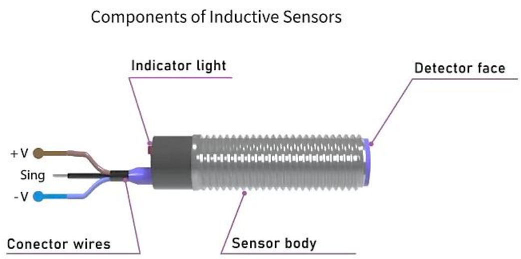

Fig. 14 Inductive sensor

Inductive sensors are robust and resistant to contamination, moisture, dust, and moderate vibrations. They do not have moving parts and therefore have unlimited mechanical lifespan. The sensing range depends on sensor size and is typically from one to twenty millimeters for standard types, although long-range versions can detect up to one hundred millimeters.
(inductive sensor)
Sensitivity depends on target material. Ferromagnetic materials such as steel provide maximum sensing range, non-ferrous metals such as aluminum and copper have reduced range by approximately half, and stainless steel has even lower sensitivity. Manufacturers specify the nominal sensing range for standard steel targets.
The design basis of the inductive sensor is a coil that creates a high-frequency electromagnetic field. This coil is part of an LC oscillator that typically operates at a frequency in the range of 100 kHz to 1 MHz. The oscillator is powered by an internal source and generates an alternating electromagnetic field radiated from the front of the sensor. This field penetrates the surrounding space and in the absence of a metal object, the oscillator operates stably with a constant amplitude.
When a metal object approaches this electromagnetic field, electromagnetic induction occurs in the conductor. According to Faraday's law of induction, a changing magnetic field induces eddy currents in the metal object. These currents create their own magnetic field oriented against the original field of the sensor, which leads to attenuation of oscillations. At the same time, eddy currents cause energy losses in the metal object, which manifests itself as additional damping of the oscillation circuit.
The sensor detection circuit monitors the amplitude of the oscillation. When the amplitude drops below a set threshold due to the presence of a metal object within the detection range, the comparator switches the sensor output signal. The distance at which switching occurs is called the detection range or reading distance.
The detection range of inductive sensors depends on several factors. The first is the size and design of the sensor's active area - larger sensors typically have a longer range. The standard detectable distance is defined for a reference metal object - a square of 1 millimeter thick iron sheet, the side of which is equal to the diameter of the sensor's active area. The actual detection range for different materials is given by a reduction factor.
The reduction factor is a multiple of the nominal detection range for a given material. Ferromagnetic materials such as iron and steel have a reduction factor close to 1,0, which means that they are detected to the full nominal range. Non-ferromagnetic

metals have lower reduction factors: stainless steel approximately 0,8 to 0,9, copper and brass approximately 0,4 to 0,5, aluminum approximately 0,4. Therefore, an aluminum object is detected at approximately half the distance compared to a steel object of the same dimensions.

Modern inductive sensors are manufactured in various designs. Cylindrical sensors with metric threads (M8, M12, M18, M30) are the most widely used in industrial automation and are mounted in metal holders. Cube sensors have a rectangular shape and are mounted using mounting grooves. Flush-mountable sensors can be installed in a metal surface without reducing the detection range, while non-flush-mountable sensors require free space around the active surface.

The output circuit of inductive sensors can be of various types. The PNP output switches the positive pole of the supply voltage, the NPN output switches the negative pole. The NO (normally open) contact closes when an object is detected, the NC (normally closed) contact opens. Many sensors include an LED indicator to indicate the output status. Some advanced models provide an analog output proportional to the distance of the object within the detection range.

In industrial applications, inductive sensors are mainly used for detecting metal parts on conveyors, counting metal products, detecting the position of metal components, monitoring the presence of tools in a machine tool, and limit switches detecting the end positions of metal parts. In CNC machine tools, they detect the presence of a workpiece in a clamping device. In automatic assembly lines, they check the correct assembly of metal components.

The advantages of inductive sensors include contactless measurement without mechanical wear, high reliability, resistance to dust, water, oil and chemicals, the ability to work in a vibration environment, insensitivity to the color and surface properties of the object and long service life. Modern sensors are resistant to short-circuiting of the output and reverse polarity of the power supply.

Disadvantages include limitation exclusively to metal objects, relatively short detection range (typically 0,5 to 15 millimeters for standard industrial sensors), dependence of the range on the type of metal, sensitivity to strong electromagnetic fields in the environment and the need to take into account minimum distances when mounting multiple sensors in close proximity to prevent mutual interference.

(Inductive sensors)

Inductive sensors are available with normally open (NO) or normally closed (NC) contacts and with PNP or NPN transistor outputs for compatibility with different control systems. Some types have an analog output proportional to distance, enabling use as proximity sensors, not just digital switches.

Applications include end position detection in pneumatic and hydraulic cylinders, object presence detection on conveyors, counting metal parts, and metal detection in security systems. In machine tools, they are used for tool and workpiece detection. In robotics, they serve for gripper position verification.

3.17 Proximity Sensors – Capacitive

Capacitive proximity sensors detect both metallic and non-metallic materials including plastics, wood, glass, liquids, and bulk materials. The principle is based on measuring changes in capacitance between the sensor electrode and ground. When an object with different permittivity than air approaches the sensor, capacitance changes, which is detected by electronics.
(capacitive sensor)
Capacitive sensors are more universal than inductive sensors because they detect almost all materials. The sensing range depends on material permittivity; materials with high permittivity such as water and metals are detected at greater distances than materials with low permittivity such as plastics and wood. Typical ranges are from a few millimeters to several centimeters.
Most capacitive sensors have adjustable sensitivity enabling adaptation to target material and desired range. Setting is usually done by a trimmer potentiometer on the sensor housing. For applications requiring detection of objects behind another material, such as liquid level through a plastic container wall, sensitivity tuning is critical.
The basic element of a capacitive sensor is a planar capacitor formed on the active surface of the sensor. This capacitor consists of two electrodes separated by a dielectric, while the electromagnetic field also penetrates into the space in front of the active surface of the sensor. The electrodes form part of an RC oscillatory circuit operating typically with a frequency in the range of hundreds of kilohertz. In the absence of an object in the detection field, the capacitor has a certain nominal capacitance and the oscillator operates at a constant frequency.
The capacitance of the capacitor is given by the well-known relation:

$$C = \frac{(\varepsilon_0 \varepsilon_\mathrm{r} A)}{d}$$

where:
C is the capacitance,
ε_0 is the permittivity of vacuum,
ε_r is the relative permittivity (dielectric constant) of the material between the electrodes,
A is the area of the electrodes, and d is the distance between the electrodes.
When an object with a dielectric constant higher than air ($\varepsilon_r = 1$) approaches the electromagnetic field of the sensor, the effective dielectric constant in the space between the electrodes increases, which leads to an increase in the capacitance of the capacitor.
This change in capacitance causes a change in the resonant frequency of the RC oscillator circuit. The evaluation circuit monitors the frequency or amplitude of the oscillations, and when the change exceeds a set threshold, the output signal of the sensor switches. The sensitivity of the detection is proportional to the dielectric constant of the material - materials with a higher ε_r are detected at a greater distance.

The dielectric constants of different materials vary significantly. Air has $\varepsilon_r \approx 1$, plastics typically have ε_r in the range of 2 to 4, glass has ε_r around 4 to 10, water has a high $\varepsilon_r \approx 80$, and metals have a theoretically infinite . Therefore, metals are best detected, followed by water and liquids with a high water content, while dry powder materials and plastics are detectable at shorter distances. The detection range of capacitive sensors is typically in the range of 2 to 40 millimeters depending on the size of the active area and the type of material being detected. For a standardized comparison, the detection range is given for a steel object similarly to that of inductive sensors. The actual detection range for other materials is then a percentage of this nominal range depending on the dielectric properties. Capacitive sensors require more careful sensitivity adjustment than inductive sensors. Most industrial capacitive sensors have a potentiometer for setting the threshold switching level. This allows the sensor to be tailored to the specific application and material, but also requires initial setup and possibly recalibration when the process changes.

A specific application of capacitive sensors is the detection of liquid levels through a non-conductive tank wall. A sensor mounted on the outside of a plastic or glass tank can detect the presence of liquid inside. Liquids with a high water content have a high dielectric constant and are easily detected, while oils and solvents with a low dielectric constant require a more sensitive setup. Another application is the detection of material inside packaging. A capacitive sensor can detect the presence of product in a paper or cardboard box, the filling of bottles with liquid, or the presence of sugar, flour, and other powdered materials in packaging. This ability to detect through non-conductive barriers makes capacitive sensors unique compared to other types.

In industrial automation, capacitive sensors are used to detect the level in tanks, check the filling of packages, detect adhesive tape on a roll (plastic adhesive tape is different from a paper core), detect the presence of various materials on conveyors, distinguish between full and empty packages and check the filling of liquids. In the field of human-machine interaction, capacitive sensors are used in touch panels and buttons. Capacitive touch displays detect the approach or touch of a finger, which has a high water content and therefore a high dielectric constant. Capacitive buttons work on a similar principle, which respond to touch without mechanical pressing.

The disadvantage of capacitive sensors is greater sensitivity to environmental conditions. Humidity, temperature changes, and contamination on the sensor surface can affect measurement. Quality sensors have automatic compensation for these influences, but setting can be more demanding than with inductive sensors.

Applications include liquid level detection in tanks and containers without mechanical contact, detection of non-metallic materials on production lines, fill verification in packaging, and bulk material level monitoring in hoppers. In food industry, they detect products through packaging.

3.18 Proximity Sensors – Ultrasonic

Ultrasonic sensors are a category of non-contact sensors that use high-frequency sound waves to detect objects and measure distance. These sensors typically operate

at frequencies in the range of 40 to 400 kHz, which is above the human ear's hearing threshold (approximately 20 kHz). The principle of operation is based on sending an ultrasonic pulse, reflecting it from the object, and measuring the return time of the reflected signal.
Ultrasonic sensors measure distance to objects based on time of flight of ultrasonic waves. The sensor emits a short ultrasonic pulse and measures time until the reflected echo returns. Since the speed of sound in air is approximately three hundred forty-three meters per second at twenty degrees Celsius, distance d can be calculated from time t.
(ultrasonic sensor)
The basic structural element of an ultrasonic sensor is a piezoelectric transducer that can convert electrical energy into mechanical vibrations and vice versa [Fig. 15]. When emitting ultrasound, an alternating voltage with the desired frequency is applied to the piezoelectric crystal, which causes it to vibrate mechanically and radiate ultrasonic waves into the surrounding environment. When receiving ultrasound, the incident sound waves cause mechanical deformations of the crystal, which generates an electrical signal detectable by an electronic circuit. Many ultrasonic sensors use a single transducer for both transmission and reception, with the electronics switching between transmission and reception modes.

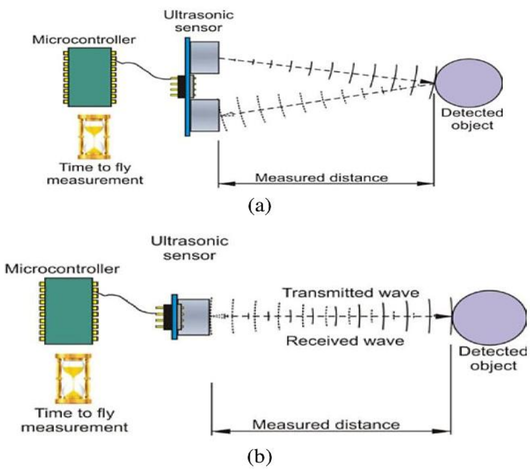

Fig. 15 Ultrasonic sensor working principle
a – top view, b – side view

Measuring distance with an ultrasonic sensor uses the same principle as ToF laser sensors, but instead of the speed of light, the speed of sound in air is used. The distance d from the object is calculated according to the relation:

$$d = \frac{(vt)}{2}$$

where:
v is the speed of sound in air and t is the measured time between the emission of the pulse and the reception of the reflection.
The speed of sound in air depends on the temperature according to the approximate relation:

$$v = 331{,}3 + 0{,}606 \cdot T$$

Ultrasonic sensors (Fig. 16) have relatively long range, typically from several centimeters to several meters. They are independent of target color and reflectivity, unlike optical sensors. They can operate in dusty and smoky environments where optical sensors fail. The disadvantage is slower response due to the finite speed of sound; measuring distance of several meters takes tens of milliseconds.

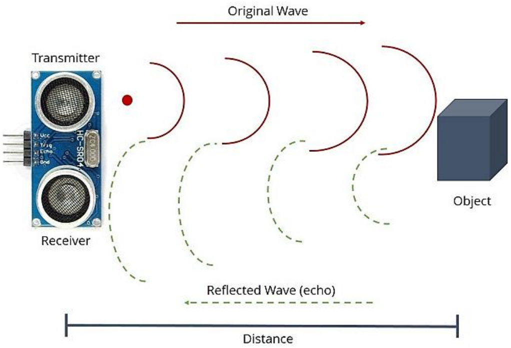

Fig. 16 Ultrasonic sensor

Temperature affects the speed of sound and therefore measurement accuracy. Quality ultrasonic sensors have integrated temperature compensation. Sensors with narrow beams (focused transducers) provide better spatial resolution but shorter range. Sensors with wide beams detect larger areas but cannot distinguish between multiple objects in the beam.

Materials absorbing ultrasound such as soft foam, fabrics, and porous materials are poorly detected. Very small objects or objects angled to the beam can reflect sound away from the sensor, causing detection failure. For reliable detection, the target should be larger than the beam diameter and oriented approximately perpendicular to the beam.

Advantages of ultrasonic sensors include their relatively low cost, ease of use, ability to detect a wide range of materials, including transparent materials, resistance to dust and dirt, and insensitivity to visual surface properties such as color or gloss. Ultrasonic sensors are not affected by lighting conditions and work equally well in the dark as in bright light.

Disadvantages include sensitivity to air temperature affecting the speed of sound, relatively slow response compared to optical sensors (on the order of milliseconds instead of microseconds), wide detection cone reducing resolution, difficulty detecting soft and absorbent materials, and the possibility of false reflections from multiple objects within the detection range. Ultrasonic sensors can also cause mutual interference if multiple sensors operate in close proximity at the same frequency.

In practical applications, ultrasonic sensors are used for liquid level detection in tanks, distance measurement in parking assistants in cars, object detection in mobile robotics, product presence control on conveyors, and a wide range of automation applications. The popular HC-SR04 sensor is often used in education and DIY projects

due to its low price and simple interface, where the duration of the output pulse directly corresponds to the measured distance.
Applications include obstacle detection in mobile robots and autonomous vehicles, liquid level measurement in tanks, material detection on conveyors, and parking sensors in vehicles. In automation, they measure distances for positioning and collision prevention.

3.19 Proximity Sensors – Optical sensors

Optical sensors represent a broad category of devices that use electromagnetic radiation in the optical region of the spectrum to detect objects, measure distance or determine position. These sensors typically operate with visible light, infrared radiation or a laser beam and use various physical principles of detection.
The basic principle of optical sensors consists in emitting light from an active source and detecting a change in the optical signal caused by the presence, distance or properties of the measured object. The light source can be a standard LED diode emitting visible light, an infrared LED operating at a wavelength of approximately 880 nanometers, or a laser diode providing a coherent and highly focused beam.Photoelectric sensors detect objects based on light emission and reception. They are divided into several types according to operating principle. Through-beam sensors have separate emitter and receiver positioned opposite each other. An object interrupting the beam between them is detected.
Retro-reflective sensors have a transmitter and receiver in one design and work with a reflector located opposite the sensor. The light is reflected from the reflector back to the receiver and the object is detected by interrupting this optical path. The reflector is a special element with retroreflective properties that reflects the light exactly back in the direction of incidence, regardless of the angle. This type allows for easier installation than through-beam sensors while maintaining high detection reliability.
Diffuse reflective sensors do not have a separate reflector and detect light scattered directly from the surface of the object. The transmitter and receiver are in one design, while the receiver detects light reflected from the object located within the detection range. The range of these sensors is relatively short (typically a few centimeters to a meter) and depends on the reflectivity of the surface of the measured object. Bright and shiny surfaces reflect more light and are detected at a greater distance than dark and matte surfaces.
The detection logic of optical sensors can operate in light or shadow mode. In light-on mode, the output is active when light is detected, while in shadow mode, the output is active when no light is detected. The choice of mode depends on the application and the requirements for safe system behavior in the event of a sensor failure.
An important parameter of optical sensors is their resistance to external light. Modern sensors use modulated light signals, where the transmitter emits light at a specific frequency (typically in the kilohertz range) and the receiver detects only the signal at this frequency. This principle significantly reduces sensitivity to external light sources

and allows reliable detection even in strong ambient lighting. This configuration provides the longest range, up to tens of meters, and highest reliability.

Retro-reflective sensors have emitter and receiver in one housing. Light is reflected by a retro-reflector and returns to the sensor. An object interrupting the beam is detected. Range is shorter than through-beam sensors, typically up to a few meters, but installation is simpler as only one cable needs to be routed.

Diffuse sensors also have emitter and receiver in one housing, but detect light reflected from the object itself. Detection range is shortest, from centimeters to a few meters, and depends on object reflectivity. Light objects are detected at greater distances than dark objects (Fig. 17).

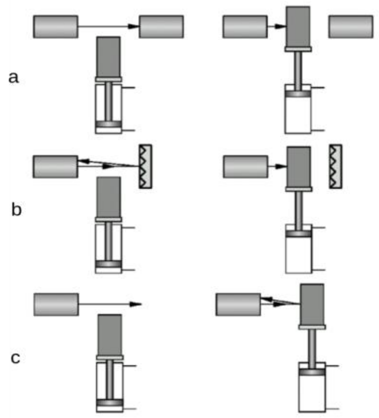

Fig. 17 Three basic types of optical sensors
a – through-beam (photocell), b – reflective, c – diffuse

Background suppression is an advanced function in diffuse sensors enabling detection of objects while ignoring background. This is achieved by triangulation or time-of-flight measurement. Sensors with background suppression can reliably detect objects at a specific distance regardless of what is behind them.

Color sensors are special photoelectric sensors distinguishing between object colors based on reflected light intensity at different wavelengths. They use RGB LEDs and multiple photodetectors. Applications include sorting of colored products, verification of labels and packaging.

Optical fiber sensors use flexible optical fibers to deliver light to hard-to-reach locations. The sensor unit contains emitter and receiver; fibers only guide light. This enables detection in confined spaces, high temperatures, and explosive atmospheres.

Advantages of photoelectric sensors are long range, fast response, high accuracy, and possibility of color and intensity detection. Disadvantages include sensitivity to contamination of optics, influence of ambient light, and problems with transparent or strongly reflective objects. Modulated infrared light is commonly used to suppress ambient light influence.

Applications are very wide, from object detection on production lines, verification of product presence, sorting by color and shape, to precise position measurement and

barcode reading. In packaging industry, they verify correct label application and packaging integrity.
In industrial automation, optical sensors are used for detecting the presence of objects on conveyors, product counting, position control, detecting marks on packaging and many other applications. Their advantages include non-contact measurement, fast response time (in the order of microseconds), long life without mechanical wear and the ability to detect a wide range of materials. The disadvantages include sensitivity to contamination of the optics by dust particles or moisture, potential interference between multiple sensors in close proximity and the influence of the surface properties of the object on the reliability of detection.

3.20 Laser sensors

Laser rangefinders are a highly accurate category of optical sensors designed for non-contact distance measurement. They use a coherent laser beam and sophisticated time or phase measurement methods to achieve accuracies in the millimetre to sub-millimetre range at ranges from a few centimetres to hundreds of metres.
(laser sensors)
The basic principle of distance measurement by laser sensors (Fig. 18) is based on two main methods.

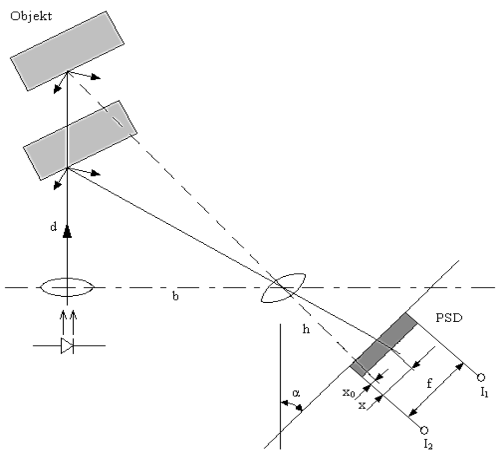

Fig. 18 Principle of the triangulation method of laser distance measurement

The first method is triangulation, used primarily for short distances with high accuracy. The laser beam strikes the surface of an object at a certain angle and the reflected light is captured by a position-sensitive detector (PSD – Position Sensitive Detector or CCD array) located at a distance from the transmitter. The position of the reflected beam on the detector changes depending on the distance to the object according to the geometric relations in the triangle formed by the transmitter, object and detector.
The distance in the triangulation method can be calculated according to the relation:

$$d = f\frac{b}{(x + c)}$$

where:

d is the object distance,
f is the focal length of the receiving optics,
b is the distance between the transmitter and receiver (base),
x is the position of the light spot on the detector, and c is a constant depending on the geometry of the system.
Triangulation laser sensors typically achieve resolutions in the range of micrometers to hundreds of micrometers with a measuring range from a few millimeters to a meter.
The second method is based on measuring the time of flight of a light pulse (ToF). A laser transmitter emits a short light pulse that is reflected from the object and returns to the receiver. The sensor electronics measure the time between sending and receiving the pulse with very high resolution. The distance is calculated from the relation:

$$d = \frac{(ct)}{2}$$

where:
d is the distance to the object,
c is the speed of light in air (approximately 3×10^8 m/s),
t is the measured flight time.
Dividing by two is necessary because the light travels the distance to the object and back. For accurate measurement, it is necessary to take into account the refractive index of air, which depends on temperature, pressure and humidity.
Modern ToF sensors use different variations of time measurement. The pulse method works with individual short pulses and directly measures their return time. The phase method uses continuously modulated laser radiation and measures the phase shift between the transmitted and received signal. The phase method allows for higher accuracies at shorter distances, while the pulse method is more suitable for long ranges of up to hundreds of meters.
The accuracy of laser rangefinders is affected by several factors. The quality of the laser and its stability determine the repeatability of the measurement. The properties of the measured surface have a significant impact – smooth and bright surfaces reflect more light and provide a better signal than rough and dark surfaces. The angle of incidence of the laser beam on the surface also affects the quality of the reflected signal – perpendicular incidence provides the best results. Atmospheric conditions, including temperature, pressure, humidity and the presence of aerosols, affect the refractive index of air and thus the accurate speed of light, which is critical for ToF measurements at long distances.
In mechatronic applications, laser distance sensors are used in a wide range of tasks. In mobile robotics, they are used for mapping the environment, detecting obstacles and navigating. A typical example is the LIDAR (Light Detection and Ranging) system, which scans the surroundings with a rotating laser beam and creates a 2D or 3D map of the environment. In industrial automation, they are used for dimensional control, level detection in tanks, position monitoring when lifting loads, and precise control of the path of moving parts. In warehouse systems, they enable precise localization of

racks and pallets. Research applications include geodetic measurements, monitoring of structural deformations, and scientific experiments requiring extremely precise distance detection. Advantages of laser distance sensors include high accuracy, long range, non-contact measurement, fast response, and the ability to measure on various types of surfaces. Disadvantages include higher price compared to other types of sensors, sensitivity to atmospheric conditions for precise measurements, the need for safety precautions when using higher-class lasers, and potential problems with transparent or strongly absorbing surfaces.

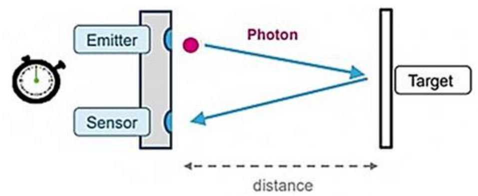

Fig. 19 Principle of the Time-of-Flight Method

3.21 Accelerometers – Principles

Accelerometers measure acceleration, which is the rate of velocity change. According to Newton's second law, force *F* acting on mass m causes acceleration a according to the relation F equals ma. Accelerometers use a test mass connected to the sensor housing through a spring or other elastic element. When the housing accelerates, the test mass lags due to inertia, creating a relative displacement or force in the elastic element. Measuring this displacement or force determines acceleration.
Three types of acceleration are measured. Linear acceleration is the rate of velocity change in a straight line. Gravitational acceleration is a constant force caused by Earth's gravity with a value of approximately 9,81 meters per second squared. An accelerometer at rest on a surface measures gravitational acceleration in the direction perpendicular to the surface. Angular acceleration is the rate of angular velocity change.
(operational principle)
Accelerometers are characterized by range, typically from a few g (gravitational acceleration units) for tilt measurement to hundreds or thousands of g for impact measurement. Resolution determines the smallest detectable acceleration change. Bandwidth indicates the frequency range in which the sensor can measure acceleration, from DC (constant acceleration) to kilohertz for high-frequency vibrations.

3.21.1 Accelerometers – Piezoelectric

Piezoelectric accelerometers use a piezoelectric element that generates charge when mechanically stressed. The test mass presses on the piezoelectric element, generating a signal proportional to force and thus acceleration. These sensors are preferred for measuring dynamic accelerations and vibrations because they have wide bandwidth and high sensitivity. The advantage is robustness, resistance to overloads, and ability to operate at high temperatures. They can measure very high accelerations without

damage. The disadvantage is inability to measure constant (DC) acceleration and need for charge amplifiers. Piezoelectric accelerometers are relatively large and heavy compared to MEMS types.
Applications include machinery and structural vibration monitoring, modal analysis for determining natural frequencies, seismology, and impact testing in automotive crash tests. In industry, they monitor bearing condition by vibration analysis, enabling predictive maintenance.

3.21.2 Accelerometers – MEMS

MEMS accelerometers are based on microelectromechanical systems technology integrating mechanical and electrical components on a silicon chip. The test mass is a suspended structure micromachined from silicon. Acceleration causes mass displacement, which is measured capacitively or piezo-resistively.
Capacitive MEMS accelerometers have interdigitated capacitor combs. One set is fixed and the other moves with the test mass. Displacement changes capacitance, which is measured by integrated electronics. Piezo-resistive MEMS accelerometers use silicon resistors changing resistance under mechanical stress.
MEMS accelerometers have dimensions of millimeters, low cost, low power consumption, and integrated electronics providing digital output. Three-axis accelerometers measure acceleration in all three orthogonal directions on a single chip. Disadvantages include lower maximum range than piezoelectric types and lower accuracy at very low frequencies.
Applications are very widespread, from smartphones and tablets for screen orientation and activity detection, through automotive systems for airbag activation, electronic stability control, to drones and robots for navigation and stabilization. Wearable devices use them for activity monitoring and health tracking.

3.21.3 Accelerometers – Applications

Integration of acceleration yields velocity and double integration yields displacement, enabling calculation of position from acceleration measurements. This principle is used in inertial navigation systems, although errors accumulate over time requiring periodic correction from other sources such as GPS.
Tilt measurement uses the fact that an accelerometer at rest measures gravitational acceleration. In a two-axis accelerometer, the angle of inclination can be calculated from measured components of gravitational acceleration. This is used in construction equipment for leveling, robotics for orientation, and electronic levels.
Vibration monitoring in machinery enables detection of failures before catastrophic damage. Bearings, gears, and motors have characteristic vibration spectra. Changes in these spectra indicate developing problems such as bearing wear, unbalance, or misalignment. Frequency analysis of vibration signals using FFT (Fast Fourier Transform) enables diagnostics and predictive maintenance.
Impact and shock detection in handling of fragile products and transportation monitoring prevents damage. Accelerometers record impacts that packages

experience, enabling identification of critical points in the logistics chain. In consumer electronics, they detect when a device falls and can activate protection, such as parking hard drive heads.

3.21.4 Gyroscopes – Principles

Gyroscopes measure angular velocity or angular position. Classical mechanical gyroscopes use a rapidly rotating mass whose spin axis maintains orientation in space according to the law of conservation of angular momentum. Rotation of the housing around the spin axis is detected as a change in orientation. Mechanical gyroscopes are precise but large, heavy, and expensive.

Modern gyroscopes use various physical principles without rotating masses. MEMS gyroscopes utilize the Coriolis effect, which causes a force perpendicular to the direction of motion when an object moves in a rotating reference frame. Optical gyroscopes detect phase shifts in light traveling opposite directions around a closed path in a rotating frame.

(gyroscope)

MEMS gyroscopes have a vibrating structure driven to oscillate in one direction (drive axis). When the sensor rotates around a perpendicular axis (input axis), the Coriolis force causes oscillation in the third perpendicular direction (sense axis). Measuring this oscillation determines angular velocity. MEMS gyroscopes are small, cheap, and have low power consumption. They are integrated with accelerometers in IMUs (Inertial Measurement Units) providing complete information about position and orientation. Disadvantages include drift over time and temperature sensitivity requiring calibration and compensation.

Applications include navigation in drones, robots, and autonomous vehicles where they provide information about rotation and orientation. In smartphones, they enable screen rotation and augmented reality. Camera stabilization systems use gyroscopes to detect camera movement and compensate for blur. Gaming controllers use them for motion detection.

Fiber optic gyroscopes (FOG) use the Sagnac effect, which is a phase shift between two light beams traveling in opposite directions around a closed loop when the loop rotates. Light from a laser is split into two beams traveling clockwise and counterclockwise through an optical fiber coil. Rotation causes one beam to travel a slightly longer path than the other, creating a phase difference proportional to angular velocity. FOG have no moving parts, are resistant to shock and vibrations, have wide bandwidth, and provide high accuracy. They are used in aircraft navigation, ships, satellites, and military systems. Disadvantages include high cost and complexity compared to MEMS gyroscopes.

IMU combines multiple accelerometers and gyroscopes to measure acceleration and angular velocity in all three axes. Typical IMU contains three orthogonal accelerometers and three orthogonal gyroscopes, providing six degrees of freedom (6-DOF). Some IMU also include a magnetometer for measuring magnetic field and determining heading, creating a 9-DOF sensor.

Data from IMU can be fused to estimate position and orientation. Kalman filters and complementary filters combine accelerometer, gyroscope, and magnetometer data to obtain stable and accurate orientation estimation. Accelerometers provide long-term stability but are sensitive to vibrations, gyroscopes provide short-term accuracy but drift over time, and magnetometers provide absolute heading but are sensitive to magnetic interference.

Applications of IMU include navigation of aircraft, ships, and land vehicles, stabilization of cameras and platforms, robotics for monitoring robot position and orientation, virtual and augmented reality for tracking user head movement, and drones for automatic stabilization and navigation.

3.22 Force and Torque Sensors

Force sensors measure mechanical force, torque sensors measure moment of force (torque) around an axis. Most force and torque sensors use strain gauges bonded to an elastic element that deforms under load. Measuring deformation determines force or torque (Fig. 20).

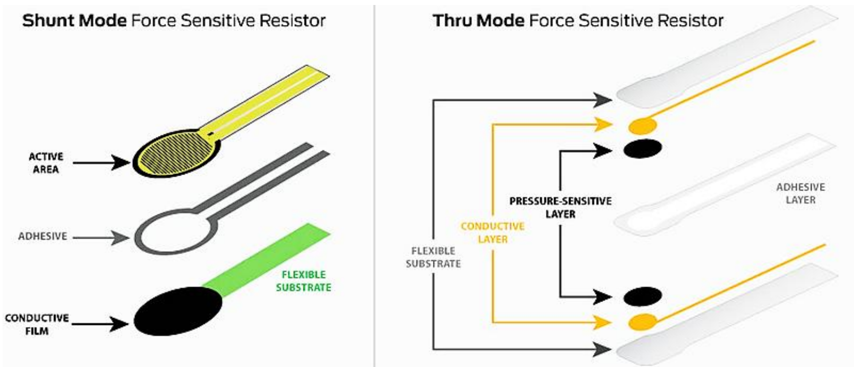

Fig. 20 Force sensors

Force sensors have various designs depending on application. Load cells for weighing use a column or beam that compresses or bends under load. Button load cells are compact and used for measuring normal forces. S-beam load cells can measure both tension and compression. Multi-axis force sensors measure forces in multiple directions simultaneously.

(force sensors)

Torque sensors measure torque transmitted through a shaft. A rotary torque sensor is mounted between a motor and load and measures shaft twist under torque. Strain gauges on the shaft surface measure torsional strain proportional to torque. Signal transfer from rotating shaft to stationary electronics is done via slip rings or wireless telemetry.

Important parameters are range, accuracy, overload protection, and operating conditions. Force sensors are designed for specific load ranges from grams to hundreds of tons. Accuracy is typically 0,1 to 1 percent of full scale. Overload protection prevents sensor damage when the maximum load is exceeded.

Applications include industrial weighing, material testing machines for measuring tension, compression, bending, and torsion properties, robotics for force control in manipulation and assembly, automotive industry for measuring propulsion forces, and medical instruments for measuring gripping forces in surgical instruments.

3.23 Flow Sensors – Principles

Flow sensors (Fig. 21) measure the amount of fluid (liquid or gas) flowing through a pipe or channel. Flow can be expressed as volumetric flow rate in cubic meters per second or mass flow rate in kilograms per second. Flow measurement is important in process industry, water management, HVAC systems, and medical applications.
Flow sensors are divided into several categories according to operating principle. Differential pressure sensors measure pressure drop across a restriction such as an orifice plate or Venturi tube. According to Bernoulli's equation, pressure drop is proportional to the square of flow velocity. Turbine flow meters use a rotor placed in the flow; rotation speed is proportional to flow.

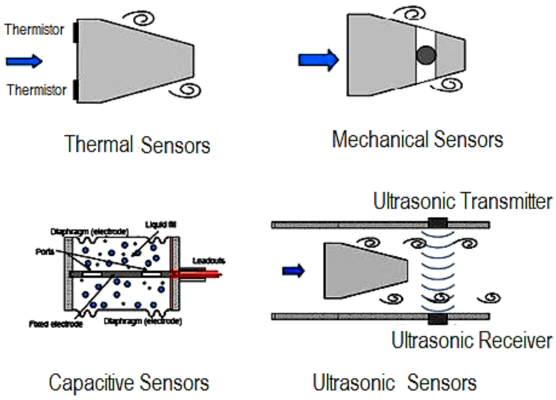

Fig. 21 Flow sensors

Ultrasonic flow meters measure fluid velocity using ultrasonic waves. Transit-time method measures the time difference of sound propagation with and against flow. Doppler method measures frequency shift of sound reflected from particles in fluid. Electromagnetic flow meters use Faraday's law of induction; conductive fluid flowing through a magnetic field generates voltage proportional to velocity.
Thermal flow sensors measure heat dissipation from a heated element. Higher flow increases cooling and decreases element temperature. Maintaining constant temperature requires more heating power, which is proportional to flow. Coriolis mass flow meters measure the Coriolis force generated by fluid flowing through a vibrating tube, providing direct mass flow measurement.
(flow sensors)
Thermal MEMS flow sensors are miniature sensors based on microelectromechanical systems technology. They contain a heated resistor and one or more temperature sensors on a silicon chip. Fluid flowing across the chip cools the heated element. Temperature distribution around the heater changes with flow rate.

In calorimetric sensors, two temperature sensors are placed symmetrically upstream and downstream of the heater. Without flow, both sensors measure the same temperature. With flow, the downstream sensor is warmer due to heat convection. The temperature difference is proportional to flow. Thermal MEMS sensors have minimal pressure drop, fast response, and can measure very low flows down to microliters per minute. They are used in medical instruments such as ventilators and anesthesia systems, analytical instruments for gas chromatography, and fuel cell systems. Disadvantages include sensitivity to fluid properties and contamination.

3.24 Humidity Sensors

Humidity sensors measure the amount of water vapor in air. Relative humidity (RH) is the ratio of actual water vapor pressure to saturation pressure at a given temperature, expressed as a percentage. Absolute humidity is the mass of water vapor per unit volume of air. Dew point is the temperature at which air becomes saturated and water begins to condense.
(humidity sensor)
Capacitive humidity sensors use a hygroscopic material whose permittivity changes with humidity. The material is placed between two electrodes forming a capacitor. Humidity change causes capacitance change, which is measured by electronics. These sensors are most common due to good accuracy, range from 0 to 100 percent RH, and reasonable cost.
Resistive humidity sensors use a material whose electrical resistance changes with humidity. They are cheaper than capacitive ones but have lower accuracy and longer response time. Thermal humidity sensors measure the thermal conductivity difference between dry and moist air.
Humidity sensor parameters include accuracy, typically 2 to 5 percent RH, response time to humidity change typically tens of seconds, operating temperature range, and long-term stability. Sensors can drift over time and require periodic calibration. Applications include climate control in buildings and greenhouses, weather stations, monitoring of storage conditions for pharmaceuticals and food, drying and humidification processes, and protection of electronics against condensation.

3.25 Gas Sensors

Gas sensors detect the presence and concentration of specific gases. They are important for safety (detecting explosive or toxic gases), environmental monitoring (emissions, air quality), and process control (monitoring chemical reactions).
Catalytic sensors for detecting combustible gases use a heated catalytic element on which the gas combusts. Combustion releases heat increasing element temperature and thus resistance. The resistance change is proportional to gas concentration. These sensors are used for detecting methane, propane, and other combustible gases.
Electrochemical gas sensors operate based on oxidation or reduction of gas on an electrode, generating current proportional to concentration. They are specific to

certain gases and used for detecting toxic gases such as carbon monoxide, nitrogen dioxide, and hydrogen sulfide. They have high sensitivity but limited lifespan.

Semiconductor gas sensors use metal oxides such as tin oxide whose conductivity changes when gases are adsorbed on the surface. Heating to several hundred degrees Celsius is required for operation. They detect various gases but are not very selective and require calibration for specific applications. Optical gas sensors use absorption of specific wavelengths of light by gases. Infrared sensors for detecting carbon dioxide and methane measure absorption in the infrared range. They are very selective and stable but more expensive.

Applications include gas leak detection in industry and households, monitoring of combustion emissions in vehicles and power plants, air quality monitoring in cities, safety in mines and chemical plants, and breath analyzers for detecting alcohol or diseases.

3.26 Magnetics sensors – Hall Effect Sensors

Hall effect sensors are a category of magnetic sensors that use the Hall effect to detect magnetic fields. This physical phenomenon was discovered by Edwin Hall in 1879 and consists in the development of a voltage perpendicular to the direction of an electric current and a magnetic field in a semiconductor or metal (Fig. 22).

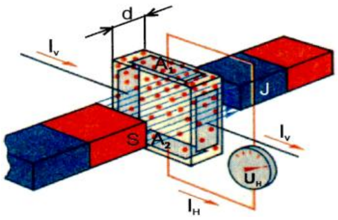

Fig. 22 Hall effect

The principle of the Hall effect can be explained in terms of the Lorentz force acting on a charge carrier moving in a magnetic field. When an electric current passes through a thin semiconductor element and the element is exposed to a magnetic field perpendicular to the direction of the current, the charge carriers (electrons or holes) are deflected to one side of the element by the Lorentz force. This deflection creates an electric potential difference between the two sides of the element, which can be measured as the Hall voltage.

The Hall voltage UH can be expressed as:

$$UH = RH \frac{(IB)}{d}$$

where:

RH is the Hall constant of the material,

I is the current flowing through the element,

B is the magnetic induction perpendicular to the current,

d is the thickness of the semiconductor element.

The Hall constant is a material property that depends on the type and concentration of charge carriers. Modern Hall sensors use semiconductors based on silicon, gallium arsenide, or indium antimony, which provide high sensitivity to magnetic fields. (Hall Effect)

There are several types of Hall sensors according to the method of signal processing. Analog Hall sensors provide an output voltage directly proportional to the magnetic field strength. These sensors are used for measuring magnetic field strength or non-contact current measurement, where the magnetic field created by the current in a conductor is proportional to the current.

Digital Hall sensors contain a comparator and provide a binary output according to the presence or absence of a magnetic field exceeding a certain threshold value. We distinguish between unipolar sensors, which respond to only one pole of the magnet (typically the south pole), and bipolar sensors, which are activated at one pole and deactivated at the opposite pole. Latch sensors remember the state even after the magnet is removed until the opposite pole is applied.

Modern Hall sensors are integrated circuits containing not only the Hall element itself, but also a signal amplifier, comparator, output transistor and sometimes temperature compensation. The output can be of the open collector, push-pull type or specialized interfaces for communication with a microcontroller.

In mechatronic systems, Hall sensors are used in a wide range of applications. One of the most common is the detection of the position of permanent magnets, where the sensor detects the approach or departure of the magnet. This is used to detect the position of the piston in pneumatic or hydraulic cylinders, where the magnet is located on the piston and Hall sensors are distributed along the cylinder body.

In brushless DC motors (BLDC), Hall sensors are a critical component for detecting the rotor position. Typically, three Hall sensors are used, spaced at 120-degree intervals, providing information about the current position of the rotor permanent magnets. This information is essential for electronic commutation - the correct timing of the stator winding phases.

Measuring the speed of rotation is another common application. A magnet or multiple magnets are attached to a rotating shaft, and a Hall sensor detects each passage of the magnet. The frequency of the output pulses is directly proportional to the speed of rotation. For greater accuracy, a gear wheel made of ferromagnetic material is used in combination with a permanent magnet and a Hall sensor, where each tooth of the wheel causes a change in the magnetic field.

Non-contact measurement of electric current uses the principle that an electric current passing through a conductor creates a magnetic field around it that is proportional to the current intensity. A Hall sensor placed near a conductor or in a magnetic yoke surrounding a conductor detects this field and provides information about the magnitude of the current without the need for an electrical connection to the circuit being measured.

Advantages of Hall sensors include non-contact measurement without mechanical wear, a wide range of operating temperatures, high reliability, resistance to dust and moisture, low power consumption, and the possibility of integration into small spaces. Hall sensors are also relatively inexpensive and easy to integrate into electronic systems.

Disadvantages include the need for a permanent magnet (indirect measurement), sensitivity to interfering magnetic fields from the environment, which can affect the accuracy of the measurement, and the temperature dependence of the sensitivity, which requires compensation for accurate measurements. The detection range is relatively short (typically a few millimeters to centimeters) depending on the strength of the magnet used.

Hall sensors are manufactured as integrated circuits with built-in Hall element, amplifier, and signal processing. Linear Hall sensors provide analog output proportional to magnetic field strength (Tab. 3). Digital Hall sensors (switches) have a digital output that changes state at a certain magnetic field threshold.

Tab. 3 Hall sensors comparation

Sensor Type	Output Signal	Dependence on Magnetic Field	Typical Application
Linear (analog)	Continuous voltage that is directly proportional to the magnetic field intensity.	The output changes continuously with changes in field intensity.	Current measurement, position detection, distance measurement.
Switching (digital)	Digital signal (on/off, high/low level).	The output changes (switches) only after exceeding a specific threshold value of magnetic field intensity.	Contactless switches, speed measurement (rpm), open/close detection.

The advantage of Hall sensors is contactless operation, unlimited lifespan, fast response, and resistance to contamination. They operate over a wide temperature range and are cheap to manufacture. Applications include position and speed detection using magnets, current measurement in conductors by measuring the magnetic field generated by current, and proximity detection.

In automotive industry, Hall sensors measure crankshaft and camshaft positions for engine management. They detect gear tooth positions for ABS and transmission control. Brushless DC motors use Hall sensors for rotor position detection. In consumer electronics, they detect phone flip cover opening/closing.

3.27 Magnetoresistive Sensors

Magnetoresistive sensors use the property of certain materials to change electrical resistance in a magnetic field. Several types of magnetoresistive effects exist differing in magnitude and origin. AMR (Anisotropic Magneto-Resistance) uses ferromagnetic alloys such as permalloy. Resistance change is several percent in typical magnetic fields (Fig. 23).

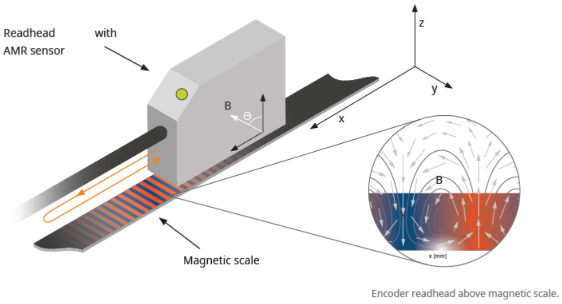

Fig. 23 Magnetoresistive sensors

GMR (Giant Magneto-Resistance) uses multilayer structures of ferromagnetic and non-magnetic layers. Resistance change can reach tens of percent, providing much higher sensitivity than AMR. TMR (Tunnel Magneto-Resistance) uses quantum tunneling through a thin insulating layer between ferromagnetic layers, providing the highest sensitivity.

Magnetoresistive sensors enable measurement of very small magnetic fields down to nanotesla. They have high spatial resolution and can be integrated on silicon chips.

Applications include reading magnetic discs in hard drives, electronic compasses in smartphones and navigation devices, and current measurement in power electronics.

GMR and TMR sensors are used in modern hard drives for reading data from magnetic disks with very high density. Reading heads must detect magnetic fields from areas of tens of nanometers. Magnetoresistive sensors have enabled significant increases in hard drive storage capacity.

3.28 Reed Sensors (Reed Switches)

Reed sensors, also known as reed switches or reed relays, represent one of the simplest and most reliable types of magnetic field sensors used in industrial automation and control systems. These sensors operate on the principle of electromagnetic switching, where the presence of an external magnetic field causes mechanical contact closure or opening within a sealed glass envelope.

(reed sensors)

The basic construction of a reed sensor consists of two ferromagnetic contact blades, typically made from nickel-iron alloy, sealed inside a glass tube filled with inert gas or vacuum. The contact blades are carefully positioned with a small gap between them, usually ranging from 0,2 to 2 millimeters. When no magnetic field is present, the contacts remain separated due to their elastic properties. Upon exposure to a sufficiently strong magnetic field, the ferromagnetic blades become magnetized with opposite polarities at their free ends, creating an attractive force that overcomes the mechanical stiffness of the blades and causes them to make electrical contact.

The switching behavior of reed sensors exhibits a characteristic hysteresis effect. The magnetic field strength required to close the contacts, known as the operate point, is higher than the field strength at which the contacts open again, called the release point. This hysteresis prevents unwanted oscillations and provides stable switching characteristics. Typical operate values range from 10 to 60 ampere-turns, while release values are approximately 50 to 80 percent of the operate value, depending on the specific sensor design and contact material.

Reed sensors offer several significant advantages in industrial applications. Their hermetically sealed construction provides excellent protection against environmental contaminants such as dust, moisture, and corrosive gases, making them suitable for harsh industrial environments. The absence of external moving parts and the sealed design result in high reliability and long operational life, with typical switching cycles exceeding 100 million operations when used within specified electrical and mechanical limits. The switching speed of reed sensors is relatively fast, with typical bounce times of 0,5 to 2 milliseconds and total switching times below 5 milliseconds, making them suitable for dynamic applications including speed measurement and position detection.

The electrical characteristics of reed sensors vary significantly depending on their size and design. Standard reed contacts can handle switching currents from a few milliamperes to several amperes, with maximum switching voltages typically ranging from 100 to 500 volts DC. The contact resistance when closed is very low, usually between 50 and 200 milliohms, ensuring minimal voltage drop and power dissipation. However, the maximum switching power is limited by the small contact area and must be carefully observed to prevent contact welding or degradation.

Industrial applications of reed sensors are diverse and numerous. They are extensively used in door and window security systems, where a permanent magnet attached to the movable part actuates the reed sensor mounted on the frame. In fluid level monitoring, float-type level switches employ reed sensors activated by magnets embedded in floating elements. Proximity detection in pneumatic cylinders represents another major application, where reed sensors detect the position of magnetic pistons through the cylinder wall without requiring physical penetration. Rotational speed measurement utilizes multiple reed sensors arranged around a rotating element equipped with magnets, generating pulse trains proportional to the rotational velocity.

Despite their advantages, reed sensors have certain limitations that must be considered during system design. The mechanical switching principle makes them susceptible to contact bounce, requiring appropriate debouncing circuits in digital applications. The contacts can be damaged by excessive inrush currents, particularly when switching inductive loads, necessitating the use of protective circuits such as series resistors or parallel suppression diodes. The switching frequency is limited compared to solid-state sensors, typically not exceeding several hundred hertz for reliable operation. Furthermore, reed sensors are sensitive to mechanical shock and vibration, which may cause false triggering or premature contact failure in high-vibration environments.

Modern reed sensor technology has evolved to include variants such as normally closed contacts, form C changeover contacts providing both normally open and normally closed connections, and mercury-wetted reed relays offering superior contact performance for low-level signal switching. The integration of reed sensors with electronic circuits has led to the development of reed relays, combining the switching element with drive coils and protective components in compact housings suitable for printed circuit board mounting.

3.29 Smart Sensors and Sensor Networks

Smart sensors are sensors with integrated microprocessor and communication interface. In addition to measuring a physical quantity, they perform signal processing, calibration, diagnostics, and communication with the control system. They can autonomously detect failures, compensate for errors, and adapt to changing conditions.

The advantage of smart sensors is automatic compensation for nonlinearities and temperature influences, self-diagnostics and reporting of failure conditions, digital communication with standardized protocols, and remote configuration. Disadvantages include higher cost and power consumption and complexity of programming and configuration.

Sensor networks connect multiple sensors into a distributed measuring system. Industrial sensor networks use standard protocols such as Profibus, Modbus, CAN, or Ethernet-based protocols like EtherCAT and Profinet. Wireless sensor networks use protocols such as Zigbee, Bluetooth Low Energy, LoRaWAN, or industrial WiFi.

IoT (Internet of Things) sensors enable connection of sensors to the Internet for remote monitoring and data analysis. Cloud platforms store and process large volumes of sensor data, enabling advanced analytics, machine learning, and predictive maintenance. Edge computing processes data directly near sensors, reducing latency and data transfer requirements.

Applications of sensor networks include environmental monitoring with distributed temperature, humidity, and pollution sensors, structural health monitoring of bridges and buildings detecting vibrations and deformations, agriculture with soil moisture and weather sensors for precision irrigation, and industrial automation with hundreds of sensors on production lines.

3.30 Sensor Fusion

Sensor fusion is the process of combining data from multiple sensors to obtain more accurate and reliable information than individual sensors can provide. Different sensors have different strengths and weaknesses; their combination can compensate for individual limitations.

For example, in IMU, accelerometers provide long-term orientation stability but are sensitive to vibrations. Gyroscopes provide accurate short-term rotation information but drift over time. Magnetometers provide absolute heading but are sensitive to magnetic interference. Sensor fusion algorithms combine these data to obtain stable and accurate orientation estimation.

Kalman filter is a recursive algorithm for estimating system state from noisy measurements. It uses a mathematical model of the system and uncertainty estimates

to optimally combine measurements from multiple sensors. Extended Kalman Filter (EKF) extends basic Kalman filter to nonlinear systems.
Complementary filter is a simpler alternative to Kalman filter combining high-pass filtered data from one sensor (gyroscope) with low-pass filtered data from another sensor (accelerometer). This effectively uses high-frequency information from the gyroscope and low-frequency information from the accelerometer.
Applications include navigation systems combining GPS, IMU, and odometry for accurate position determination even during GPS signal loss, autonomous vehicles fusing data from cameras, lidars, radars, and ultrasonic sensors for environment detection, and robotics combining multiple sensors for mapping and localization.

3.31 Sensor Calibration and Diagnostics

Calibration is the process of determining the relation between sensor output and the actual value of the measured quantity. Even quality sensors have production tolerances, temperature influences, and aging effects that cause deviations from ideal characteristics. Calibration establishes correction factors enabling accurate measurement.
One-point calibration is the simplest method correcting only offset (zero error). The sensor is exposed to a known reference value and the difference between measured and actual value is recorded. This correction is then added to all subsequent measurements. One-point calibration is suitable for sensors with good linearity where only offset changes, such as from temperature drift.
Mathematically, one-point calibration is expressed by adding a correction constant:

$$y_{cal} = y_{mer} + k$$

where:
y_{cal} is the calibrated value, ymer is the measured value,
k is the correction constant determined as the difference between the reference value and measured value at the calibration point.
Two-point calibration is the most common method using two reference points, typically near the lower and upper limits of the measuring range. This method corrects both offset and gain, compensating for incorrect slope of the characteristic. Two-point calibration assumes a linear relation between actual value and sensor output.
The mathematical relation for two-point calibration is:

$$y_{kal} = ay_{mer} + b$$

where:
a is the gain correction factor,
b is the offset correction factor.
These constants are determined by solving a system of two equations from two calibration points:

$$y_{ref1} = ay_{mer1} + b$$
$$y_{ref2} = ay_{mer2} + b$$

Solving yields:

$$a = \frac{(y_{ref2} - y_{ref1})}{(y_{mer2} - y_{mer1})}$$
$$b = y_{ref1} - a y_{mer1}$$

Multi-point calibration uses three or more reference points distributed across the measuring range. This method is necessary for sensors with nonlinear characteristics, such as thermocouples. Correction is implemented using a lookup table (LUT) or polynomial fit.

When using a lookup table, the measured value is found between the two nearest calibration points and the correct value is determined by linear interpolation. For a value ymer between points $(y_{mer\,i}, y_{ref\,i})$ and $(y_{mer\,i+1}, y_{ref\,i+1})$:

$$y_{kal} = y_{(refi)} + (y_{mer} - y_{(meri)}) \cdot \left(\frac{y_{(refi+1)} - y_{(refi)}}{y_{(meri+1)} - y_{(meri)}} \right)$$

Polynomial approximation fits calibration data with a polynomial of degree n:

$$y_{kal} = a_0 + a_1 \cdot y_{mer} + a_2 \cdot y_{mer^2} + \ldots + a_n \cdot y_{mer}^n$$

Coefficients a_0 through an are determined by the least squares method from calibration data. Higher-degree polynomials provide better accuracy for nonlinear sensors but require more calibration points and computational power

The calibration process requires reference standards of higher accuracy than the calibrated sensor, typically at least three times higher accuracy. Precision manometers or calibration pumps are used for pressure sensor calibration. Thermal sensors are calibrated in precisely controlled thermostats or using reference points such as the boiling point of water (100°C at standard atmospheric pressure) or the melting point of ice (0°C). Position sensors require precise mechanical reference positions measured with gauge blocks or laser interferometers.

The calibration environment has significant influence on calibration results. Temperature, humidity, vibrations, and electromagnetic interference can affect measurement during calibration. Therefore, critical calibrations are performed in controlled laboratory conditions with regulated temperature and low vibration. Calibration frequency depends on sensor type, operational stress, and accuracy requirements. Critical measuring systems in medical devices or laboratories require calibration every few months. Industrial sensors in stable conditions may have a calibration interval of one to two years. Certified calibrations required by regulatory standards must be performed by accredited laboratories and documented with calibration protocols.

Auto-calibration is a function of some modern sensors that contain internal reference elements and electronics capable of performing calibration without external intervention. Some digital sensors perform internal calibration at each power-up or periodically during operation.

Sensor diagnostics includes monitoring and verification of proper sensor function during operation. Basic diagnostic methods check physical sensor parameters. Sensor integrity check verifies that the sensor responds to communication requests and provides valid data. Wire breaks, shorts, or power failures manifest as error states.

Zero drift test checks sensor output at known zero value of the measured quantity. Zero drift above a certain limit indicates need for recalibration or sensor replacement. This test can be performed automatically at times when the measured quantity is known to be zero.
Repeatability of measurement is tested by repeated measurements of the same value. High variability in repeated measurements indicates problems with the sensor or interference in the measurement chain.
Outlier detection identifies measurements that differ significantly from expected values or trends. Outliers can indicate transient faults, electromagnetic interference, or beginning sensor failure.
Trending and prognostics monitor long-term changes in sensor characteristics over time. Gradual parameter drift can indicate sensor aging and enable predictive maintenance – sensor replacement before complete failure. Advanced diagnostic methods use redundant sensors measuring the same quantities. Comparison of redundant sensor outputs can identify which sensor is providing erroneous data. Voting algorithms can automatically ignore output from a faulty sensor and use values from healthy sensors.
Built-in self-test (BIST) is a function of some intelligent sensors that contain circuits for generating test signals and verifying proper function of the measurement chain. When BIST is activated, the sensor switches from normal measurement to test mode, where an internal generator creates a known signal and the circuit verifies that the output corresponds to the expected value.
Implementation of diagnostics in control systems requires careful design. Overly sensitive alarms create false alarms and reduce operator confidence. Overly tolerant diagnostics do not detect real problems in time. Thresholds for diagnostic alarms must be set based on statistical analysis of operational data and understanding of possible failure modes.

4 ACTUATORS – ELECTRIC

Electric actuators represent the most widespread type of drives in mechatronic systems. Their dominance stems from several reasons, including good controllability, a wide power range from milliwatts to megawatts, relatively high efficiency, and ease of integration into control systems. The basic function of an electric actuator is to convert electrical energy into mechanical motion or force, and this process occurs through electromagnetic induction and utilization of the Lorentz force.

4.1 Electric Actuators – Introduction and Classification

The basic classification of electric actuators [Fig. 24] is based on the type of motion performed. Rotary motors are the most common type and execute rotational motion, which can be further transformed into linear motion using mechanical transmissions. Linear actuators directly perform rectilinear motion without the need for transmission mechanisms, thereby increasing precision and reducing mechanical system complexity. Further classification concerns the type of supply voltage and the motor's operating principle.

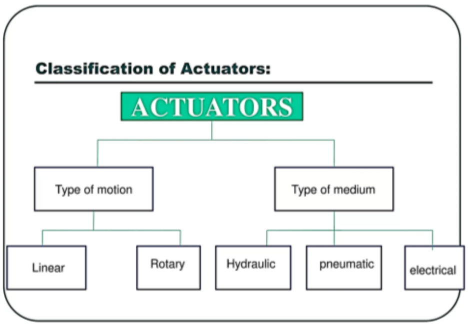

Fig. 24 Classification of actuators

Direct current motors, designated as DC motors, work with direct current voltage and use current commutation to create a rotating magnetic field. Alternating current motors, designated as AC motors, are powered by alternating voltage and directly utilize a rotating magnetic field created by multi-phase voltage. Stepper motors represent a special category that combines properties of both types and allows discrete rotation in precisely defined steps. Servo motors are not a separate category from the standpoint of operating principle but represent a complex system consisting of a motor, position sensor, and control electronics with closed-loop feedback.

The selection of the appropriate motor type depends on specific application requirements. Key parameters for selection include the required torque that the motor must develop under a given load, maximum and operating rotational speed, positioning accuracy and motion repeatability, dynamic properties such as acceleration and deceleration, energy conversion efficiency, motor weight and dimensions, acquisition and operational costs, available supply voltage, and maintenance requirements. Each motor type has its advantages and limitations that predetermine it for certain application areas.

4.2 DC Motors – Operating Principle

The direct current motor with brushes (Fig. 25), designated in English literature as brushed DC motor, represents historically the first type of electric motor and still finds wide application thanks to its constructional simplicity.

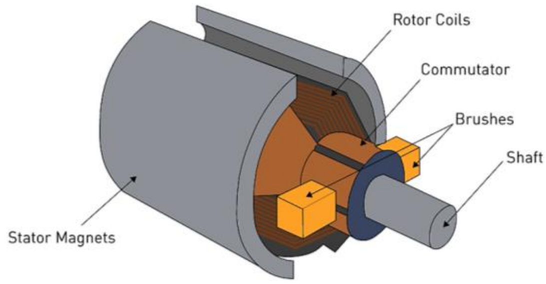

Fig. 25 DC motor

The operating principle of this motor is based on the Lorentz force, which acts on a current-carrying conductor placed in a magnetic field. The force acting on the conductor is proportional to the magnitude of electric current passing through the conductor, the magnetic field intensity, and the effective length of the conductor in the magnetic field.

Structurally, the DC motor consists of several basic parts. The stator forms the outer part of the motor and contains permanent magnets or electromagnets that create a radial magnetic field. The rotor, also designated as the armature, is mounted on the shaft and contains winding arranged in several coils. The commutator is a cylindrical body attached to the shaft, which is divided into segments electrically connected to the respective rotor coils. Brushes, typically carbon, are fixed contacts pressed against the commutator by springs, which ensure electrical connection between the stationary external circuit and the rotating winding.

(operating principle)

The function of the commutator is crucial for understanding the DC motor principle. As the rotor rotates, the commutator segments progressively come into contact with the brushes, thereby periodically changing the polarity of current passing through individual coils. This mechanical commutation ensures that the force acting on the coils always points in the same direction relative to the stator's magnetic field, thereby achieving continuous rotor rotation. Without the commutator, the rotor would only rotate half a revolution and would remain in a stable position.

The electrical behavior of the DC motor can be described using basic relations. The electromotive voltage, designated as back-electromotive force or back-EMF, is induced in the rotor winding as it rotates in the magnetic field. This voltage is proportional to the angular rotational velocity and magnetic field intensity according to the relation:

$$U_{emf} = k_e \Phi \omega$$

where:

k_e is the motor constant dependent on its construction,

Φ is the magnetic flux, and ω is the angular velocity in radians per second.

The torque developed by the motor is proportional to the current passing through the winding:

$$M = k_t \Phi I$$

where:
k_t is the torque constant,
I is the winding current.
For motors with permanent magnets, the constants ke and kt are numerically equal, differing only in dimensional units.
The advantages of DC motors with brushes lie in their simple construction and low manufacturing costs. Speed control is direct and intuitive because the rotational speed is almost linearly dependent on the supply voltage, while torque is directly proportional to current. They do not require complex control electronics and can be controlled by simple circuits. The motor's mechanical characteristic is naturally descending, meaning that as load increases, speed slightly decreases, which in many applications represents an advantage.
The disadvantages of these motors are primarily related to the presence of brushes and commutator. Mechanical wear of brushes and commutator leads to limited lifespan and the need for regular maintenance. Sparks arising during commutator segment switching cause electromagnetic interference, which can interfere with surrounding electronics. Efficiency is lower compared to modern brushless motors, typically in the range of seventy-three to eighty-five percent. Mechanical wear worsens at higher rotational speeds and in dusty environments.
Application areas of DC motors with brushes include consumer electronics, where low cost and simplicity outweigh lifespan requirements. They are found in handheld tools, toys, automotive applications such as window lifts and seat adjustments. In industry, they are used where maintenance requirements are not critical and electromagnetic interference is not a problem. Despite the development of brushless technologies, DC motors with brushes maintain their place in applications where their advantages outweigh the disadvantages.

4.3 Brushless DC motors (BLDC)

The brushless DC motor, designated in English literature as BLDC or brushless DC motor, represents a modern alternative to the classic DC motor with brushes. The basic principle of electromagnetic energy conversion remains the same, but the commutation method is fundamentally different. Instead of mechanical commutation using brushes and commutator, electronic commutation implemented by power electronics is used. This change brings significant improvement in motor properties and expands its application possibilities. The structural arrangement of the BLDC motor is opposite compared to the brushed motor. Permanent magnets are placed on the rotor, while the winding is located in the stator. This arrangement, designated as outrunner or inrunner depending on whether the rotor rotates outside or inside the stator, allows simpler rotor construction and better winding cooling. The stator winding is typically three-phase, arranged in three separate coils or groups of coils

offset by one hundred twenty degrees. The permanent magnets on the rotor are arranged to create alternating north and south poles.
(operating principle)
For proper BLDC motor function (Fig. 26), it is essential to know the current rotor position in order to correctly switch the stator winding phases.

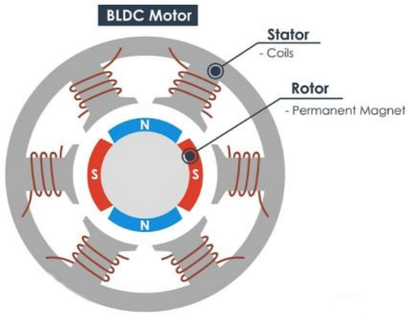

Fig. 26 BLDC motor

Two basic approaches exist for position detection. The first approach uses Hall sensors, which are placed on the stator and detect the magnetic field of the rotor's permanent magnets. Typically, three Hall sensors offset by sixty degrees are used, providing six discrete states during one electrical revolution. This approach is reliable and simple to implement but adds additional components and cables. The second approach, designated as sensorless, uses measurement of back-electromotive voltage in unpowered phases to detect rotor position. This method eliminates the need for additional sensors but requires more sophisticated control electronics and has problems at low speeds.
The electronic controller, designated as ESC from English Electronic Speed Controller, is a key component of the BLDC motor system. The ESC contains six power transistors connected in a three-phase bridge configuration, which enable switching of current through individual stator winding phases. The microprocessor in the ESC evaluates signals from Hall sensors or back-electromotive voltage and based on this generates appropriate signals for controlling power transistors. The commutation sequence proceeds in six steps during one electrical revolution, with two phases being powered and the third phase disconnected in each step.
The advantages of BLDC motors are significant compared to brushed motors. Lifespan is significantly longer because there are no wearing mechanical contacts, allowing tens of thousands of operating hours. Efficiency is higher, typically above ninety percent, thanks to elimination of brush losses and better winding cooling. The power-to-weight ratio is better because rotor magnets are lighter than winding and commutator. Operation is quiet without sparking and mechanical noise from brushes. Dynamic properties are better thanks to lower rotor inertia. No electromagnetic interference from the commutator is generated.
The disadvantages of BLDC motors lie primarily in higher acquisition costs, which include not only the motor itself but also the electronic controller. Control electronics are more complex and require a programmed microprocessor or specialized circuit.

With the sensorless variant, there are problems with starting from standstill and at very low speeds. Power electronics generate high-frequency interference from PWM switching. Repair costs are higher because electronics cannot be repaired in the field. BLDC motor applications are extensive and continuously expanding. In drones and flying models, BLDC motors are almost exclusively used thanks to their high power-to-weight ratio. In electric vehicles and electric bicycles, they represent the standard solution for traction drive. In CNC machine tools and robotics, they are used as servo drives. In computer fans and hard drives, they ensure quiet and reliable operation. In household appliances such as dishwashers and washing machines, they are beginning to replace classic motors. In medical instruments, their advantage is the absence of sparks and low interference.

4.3.1 PWM Control of DC Motors

Pulse-width modulation (Fig. 27), designated by the acronym PWM from English Pulse Width Modulation, represents an efficient method of DC motor speed control.

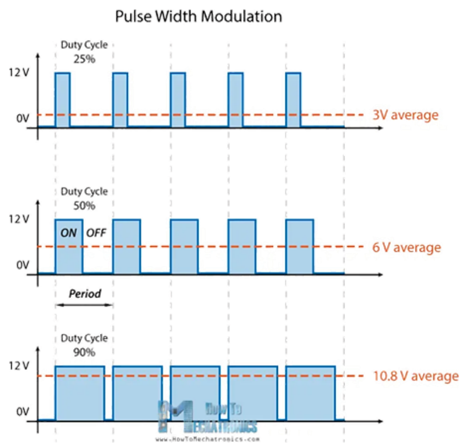

Fig. 27 PWM regulation

The PWM principle consists of rapid switching of supply voltage between on and off states, with the average voltage value being determined by the ratio of time during which voltage is on to the total signal period. This ratio, designated as duty cycle, is expressed as a percentage or as a decimal number in the range from zero to one.
(operation)
Mathematically, the average voltage value can be expressed as the product of supply voltage and duty cycle. At a duty cycle of fifty percent, the average voltage equals half the supply voltage. At a duty cycle of seventy-five percent, the average voltage equals three-quarters of the supply voltage. The motor behaves as if powered by constant voltage equal to this average value because the motor's electrical and mechanical inertia acts as a low-pass filter that smooths rapid voltage changes.
The PWM signal frequency is a critical parameter for proper system function. At too low a frequency, the motor cannot smooth the pulses and unpleasant mechanical vibrations and audible whistling occur at the PWM frequency. At too high a frequency, switching losses in power transistors increase. The typical PWM frequency for motor

control ranges from two to twenty kilohertz. This frequency is sufficiently high for the motor to act as a mechanical filter, but not so high as to cause excessive switching losses.
PWM control implementation requires a power switching element, which is typically a MOSFET transistor for lower powers or IGBT for higher powers. The transistor must be dimensioned to withstand the motor's maximum current and supply voltage. For transistor protection, a flyback diode is usually connected in parallel with the motor, which diverts inductive currents arising when the motor winding is switched off. PWM signal generation is provided by a microprocessor or microcontroller that has built-in peripherals designed for this purpose.
Direction of DC motor rotation can be changed by reversing the voltage polarity on the motor terminals. For electronic control of rotation direction, an H-bridge configuration is used, which consists of four power transistors allowing current flow through the motor in both directions. The designation H-bridge comes from the circuit's appearance, which resembles the letter H, with the motor located in the center horizontal bar. By suitable control of transistors in the H-bridge, it is possible to achieve three basic operating modes: rotation in one direction, rotation in the opposite direction, and active braking.
Active braking of the motor can be realized in several ways. Dynamic braking short-circuits the motor terminals through a resistor, causing the motor to act as a generator and mechanical energy is converted to electrical energy dissipated in the resistor. Regenerative braking returns energy back to the power supply, which is advantageous in battery-powered applications but requires bidirectional power supply capability. In both cases, braking is more effective than simple mechanical friction and allows faster motor stopping.

4.4 Stepper Motors

Stepper motors (Fig. 28), represent a special category of electric motors that execute motion in precisely defined angular steps.

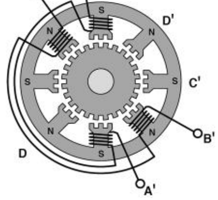

Fig. 28 Stepper motor

The basic characteristic of a stepper motor is that its rotor does not rotate continuously but moves in discrete increments, called steps, with each step corresponding to a defined angle typically in the range from zero point nine to fifteen degrees. This property makes stepper motors ideal for applications requiring precise positioning without the need for feedback sensors.The operating principle of the stepper motor is based on sequential energizing of stator winding phases, which create a rotating magnetic field moving in discrete steps. The permanent magnet rotor or rotor with teeth aligns with the magnetic field created by the currently energized phase. By systematic phase switching in a suitable sequence, gradual rotor rotation is achieved. The number of steps per revolution depends on motor construction and the method of controlling the winding.

4.4.1 Types of Stepper Motors

Stepper motors are classified into three basic types according to rotor construction. Permanent magnet stepper motors have a rotor made of permanent magnets with several pole pairs. These motors have a relatively large step, typically seven point five to fifteen degrees, meaning forty-eight to twenty-four steps per revolution. They are simple, inexpensive, but have lower torque and positioning accuracy. They find application in inexpensive positioning systems and consumer electronics.
(working principle)
Variable reluctance stepper motors have a rotor made of soft magnetic material with teeth, without permanent magnets. The rotor aligns in a position where magnetic circuit reluctance is minimal. These motors have a smaller step, typically three to fifteen degrees, and can achieve higher torque than permanent magnet motors. The disadvantage is the absence of holding torque when unpowered. They are used in applications where high torque and precision are required but maintaining position after power-off is not critical.
Hybrid stepper motors combine principles of permanent magnet motors and variable reluctance motors. The rotor contains permanent magnets and also has toothed structure. These motors achieve the smallest step, typically zero point nine to one point eight degrees, meaning four hundred to two hundred steps per revolution. They provide the highest torque, best positioning accuracy, and good holding torque. Hybrid motors are the most common type in industrial applications and represent a standard in precise positioning systems.

4.4.2 Stepper Motor Control Methods

The basic control method is full-step control, where in each step one or two phases are energized according to a defined sequence. With single-phase energizing, only one phase is active at each moment, resulting in lower torque but lower power consumption. With two-phase energizing, two phases are always active simultaneously, providing higher torque and better position stability. The step angle is determined by motor construction and is the same for both variants.
Half-stepping represents a control method that allows doubling the number of steps per revolution. The control alternates between states where one phase is energized and states where two phases are energized. This leads to intermediate rotor positions between full-step positions. Half-stepping improves motion smoothness and increases positioning resolution but somewhat reduces maximum torque in intermediate positions.

Microstepping is an advanced control method that allows dividing one full step into many smaller microsteps, typically from four to two hundred fifty-six microsteps per step. This is achieved by controlling phase currents with different amplitudes using pulse-width modulation. Appropriate current combination in two phases allows setting the rotor to any intermediate position. Microstepping significantly improves motion smoothness, reduces vibration and noise, and increases positioning resolution. However, at higher microstep divisions, positioning accuracy is limited by motor nonlinearities and friction.

4.4.3 Control Electronics for Stepper Motors

Control electronics for stepper motors must ensure the correct sequence of phase energizing and appropriate current magnitude in individual phases. The basic component is the stepper motor driver, which contains power transistors for switching current through windings and logic circuits for generating the correct commutation sequence. Modern drivers are integrated circuits that contain all necessary functions including current regulation, protection against overcurrent and overheating, and microstep control (Fig. 29).

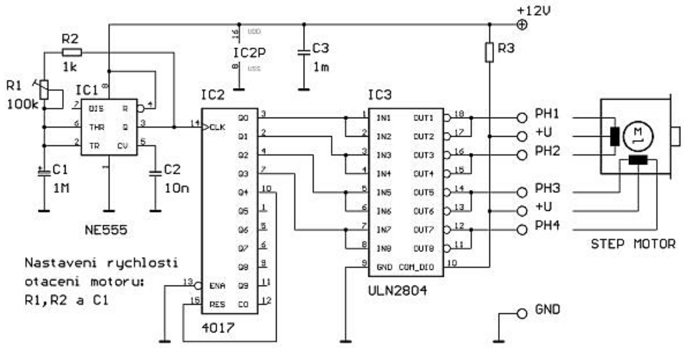

Fig. 29 Stepper motor controll

The control signal for the driver usually consists of two signals: step and direction. Each pulse on the step input causes the motor to move by one step in the direction determined by the logic level on the direction input.

This simple interface allows easy connection to microcontrollers and industrial control systems. Some drivers also offer an enable signal for motor activation/deactivation and inputs for setting parameters such as microstep division and current magnitude.

Current control in stepper motor phases is essential for proper function. Too low current leads to torque loss and possible step skipping. Too high current causes overheating and energy waste. Modern drivers use current regulation that maintains constant current in the winding regardless of rotational speed and back-electromotive voltage. Current is typically set by external resistor or digital input according to motor requirements (Fig. 30).

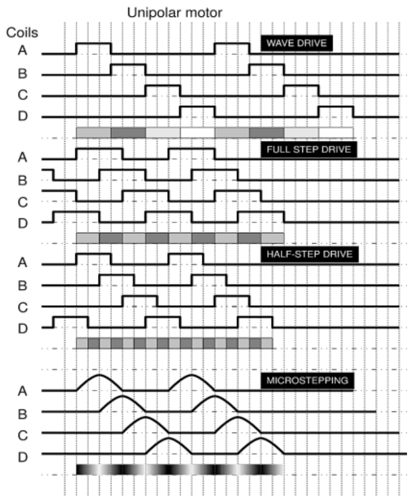

Fig. 30 Stepper motor characteristics

4.4.4 Stepper Motor Characteristics

The torque characteristic of a stepper motor shows dependence of available torque on rotational speed. At standstill and low speeds, the motor provides maximum holding torque, which is the torque the motor can resist without losing position. As speed increases, available torque decreases due to winding inductance, which limits the rate of current change in phases. At high speeds, the torque can drop to tens of percent of the holding torque value.

Resonance is an undesirable phenomenon that can occur at certain rotational speeds. The natural frequency of the mechanical system formed by the rotor, load, and coupling can coincide with the stepping frequency, resulting in vibration amplification and possible step loss. Resonance can be suppressed by using microstepping, mechanical dampers, or avoiding critical speeds. Modern drivers often include anti-resonance functions.

Positioning accuracy of stepper motors depends on several factors. The basic step accuracy is given by motor construction and is typically plus minus three to five percent of the step angle. Mechanical play in transmission and coupling further reduces accuracy. Microstepping improves resolution but does not necessarily improve absolute accuracy due to nonlinearities in the motor magnetic circuit. For applications requiring high absolute accuracy, feedback sensors and closed-loop control are necessary.

4.4.5 Applications of Stepper Motors

Stepper motors are widely used in three-dimensional printers, where they ensure precise positioning of the print head and print bed. Their advantage is the possibility of open-loop control without the need for expensive encoders. Typical three-dimensional printers use hybrid motors with one point eight degree step and microstepping division one sixteenth to one thirty-second of the step.

In CNC machines and plotters, stepper motors are used for axis drives in applications where maximum speed and power are not critical. For smaller desktop CNC machines,

stepper motors represent a cost-effective alternative to servo drives. Holding torque when unpowered is an advantage for maintaining position when work is paused.
Medical instruments such as infusion pumps and laboratory dispensers use stepper motors for precise dosing. Accurate and repeatable positioning allows achieving required precision in medication or reagent dispensing. Quiet operation and the possibility of low-speed operation without additional gears are additional advantages.
Optical instruments including cameras with autofocus, microscopes, and telescopes use small stepper motors for lens positioning. Precise step division allows fine focusing, and the absence of position sensor reduces cost and complexity of the mechanism.

4.5 Servo Motors and Servo Drives

Servo motors represent electric motors equipped with position feedback and control electronics that allow precise positioning and speed control. The term servo comes from Latin servus meaning servant, which expresses the motor's ability to faithfully follow command signals. Unlike stepper motors, servo motors work in a closed feedback loop, which allows achieving higher accuracy, better dynamic properties, and the ability to compensate for load disturbances.
(working principle)
The basic servo system consists of several key components. The motor itself can be a DC motor with brushes, BLDC motor, or AC synchronous motor. The position sensor, most often an encoder or resolver, measures actual rotor position and speed. The control electronics, called a servo drive or servo amplifier, compares the desired position with actual position and generates appropriate motor control signals to minimize position error. Communication interface allows transmission of command signals from a higher control system (Fig. 31).

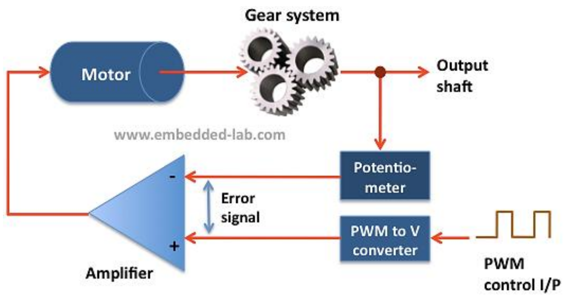

Fig. 31 Servo motor controll

4.5.1 Types of Servo Motors

DC servo motors with brushes were historically the first type of servo motors. Their advantage is simple control and good dynamic properties. The disadvantage is the presence of brushes, which limit lifespan and cause electromagnetic interference. Currently, they are used mainly in applications where low cost is critical and limited lifespan is acceptable.

BLDC servo motors represent the modern standard for most applications. They combine the advantages of DC motors, such as linear torque characteristics, with the advantages of brushless construction – long lifespan, high efficiency, and minimal maintenance. Power electronics for BLDC motors are more complex, but modern integrated drivers enable simple implementation.

AC servo motors use synchronous motors with permanent magnets on the rotor and three-phase winding on the stator. They are similar to BLDC motors but are typically designed for higher powers and use sinusoidal winding and field-oriented control. AC servo motors are used in demanding industrial applications requiring high power, wide speed range, and excellent dynamic properties.

Linear servo motors represent a special category that directly produces linear motion without mechanical conversion from rotary motion. Their principle is similar to rotary motors but the stator and rotor are "unwrapped" into a linear configuration. Linear motors eliminate mechanical play, friction, and wear associated with transmissions and allow achieving very high speeds and accelerations. They are used in high-speed CNC machines, semiconductor manufacturing, and precise positioning systems.

4.5.2 Position and Speed Sensors

The optical incremental encoder is the most common position sensor in servo systems. It consists of a rotating disk with radial stripes and optical sensors that detect the passage of stripes. The encoder generates two signals offset by ninety degrees, which allows determining not only position but also direction of rotation. Resolution is given by the number of stripes on the disk and can reach thousands of pulses per revolution. Additional index signal marks one specific position per revolution.

The absolute encoder provides information about absolute position without the need to find a reference position after power-up. Encoding can be binary, Gray code, or other code. Multi-turn absolute encoders can track position through multiple revolutions using additional mechanical or electronic gears. Absolute encoders are more expensive than incremental ones but are necessary in applications where loss of position information during power failure is unacceptable.

Resolvers are electromagnetic sensors that use the principle of rotating transformers. They are robust, resistant to harsh environments including high temperatures, vibrations, and electromagnetic interference. They provide analog signal that requires special electronics for processing. Resolvers are used in demanding industrial applications, in the automotive industry, and in aerospace.

Hall sensors in combination with a magnetic disk can serve as low-cost position sensors for less demanding applications. Resolution is lower than with optical encoders, but the sensor is robust and resistant to contamination. This solution is often used in BLDC motors for commutation and basic speed control.

4.5.3 Servo Drive Control

The basic control element of a servo drive is a PID controller (Proportional-Integral-Derivative), which generates a control signal based on position error. The proportional component provides response proportional to current error. The integral component eliminates steady-state error by accumulating error over time. The derivative component responds to the rate of error change and improves system dynamics.

Velocity control is often used as an inner loop in cascade control structure. The position controller generates a required velocity, which is then tracked by the velocity controller. This two-level control allows better optimization of dynamic properties and disturbance rejection. Some servo drives also include a current controller as the innermost loop.

Modern servo drives use advanced control methods such as field-oriented control for AC and BLDC motors, which allows independent control of torque and flux. Feedforward control improves tracking of fast-changing reference signals. Adaptive controllers can adjust parameters based on changing load conditions. State observers estimate variables that are not directly measured.

4.5.4 Characteristics and Performance

The positioning accuracy of servo systems can reach fractions of arc seconds for precise applications. Repeatability, which expresses variability of positioning to the same position, is usually better than absolute accuracy. Servo systems can compensate for systematic errors such as gear play or transmission nonlinearities through software calibration.

Dynamic properties include maximum acceleration and deceleration, response time to command change, and settling time. High-performance servo drives can achieve accelerations of tens of G and response times in milliseconds. Bandwidth of the control loop, expressing the frequency at which the system can still track reference signal, reaches hundreds of Hertz.

Torque capability includes continuous torque that the motor can provide indefinitely without overheating and peak torque available for short time periods during acceleration. The ratio of peak torque to continuous torque is typically two to three to one. Overload capacity is an important parameter for applications with variable load.

4.5.5 Applications

CNC machine tools use servo motors for all axes. Precise positioning combined with high dynamics allows achieving high machining accuracy and productivity. Spindle drives also often use servo motors instead of classic asynchronous motors. Communication networks such as EtherCAT enable synchronized motion of multiple axes.

Industrial robots require servo motors in all joints. Six-axis robots typically use six servo motors with different power and speed ranges. Requirements for dynamic

properties are extreme, especially for palletizing and handling robots. Integrated cable routing through joints minimizes wear and simplifies maintenance.
Packaging machines and printing machines require synchronized motion of multiple axes at high speeds. Electronic camshafts replace mechanical cams and allow flexible setting of motion profiles. Position synchronization between individual mechanisms must be precise to fractions of a millimeter at speeds of meters per second.
Semiconductor manufacturing and electronics assembly require extremely precise positioning at microscale. Vacuum compatibility and minimal particle generation are critical requirements. Linear motors and air bearings allow achieving required accuracy without mechanical contact.

4.6 AC Asynchronous Motors

Asynchronous motors (Fig. 32), also called induction motors, represent the most widespread type of electric motors in industrial applications.

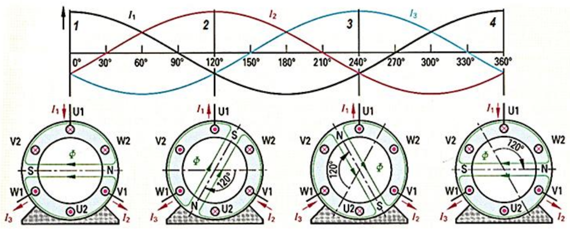

Fig. 32 AC asynchronous motor

Their dominance stems from robust construction, simple maintenance, high reliability, and good efficiency. Unlike synchronous motors, the rotor of an asynchronous motor rotates at a speed lower than the rotating magnetic field speed, hence the designation asynchronous.
(working principle)
The operating principle is based on electromagnetic induction. The three-phase winding in the stator, powered by three-phase alternating voltage, creates a rotating magnetic field. This field rotates at synchronous speed determined by supply frequency and the number of pole pairs. The rotating magnetic field induces voltage in the rotor winding or in conductive rotor bars, which causes current to flow. The current in the rotor creates its own magnetic field, which interacts with the stator's rotating field.
The interaction of magnetic fields results in torque acting on the rotor. For torque to exist, the rotor must rotate at a speed different from the synchronous speed. The difference between synchronous speed and actual rotor speed is called slip. Slip is expressed as a percentage of synchronous speed and typically amounts to two to five percent at rated load. At no load, slip is minimal, and the rotor rotates at a speed close to synchronous. As load increases, slip increases, which allows the motor to develop greater torque.

Squirrel cage motors have a rotor made of aluminum or copper bars that are short-circuited by end rings. This construction resembles a squirrel cage, hence the name. Squirrel cage motors are robust, inexpensive, and require no maintenance of the rotor. They are the most common type and are used for most industrial applications. The disadvantage is limited starting torque and high starting current, which can be five to seven times the rated current.

Slip ring motors have a rotor with three-phase winding that is connected through slip rings and brushes to external resistors. This allows control of rotor resistance, which improves starting properties and allows speed regulation. Starting torque can be high with relatively low starting current. The disadvantage is the presence of slip rings and brushes, which require maintenance. Slip ring motors are used in applications requiring high starting torque, such as cranes and mills.

Single-phase asynchronous motors are designed for connection to single-phase networks, typically in household and small appliances. Since a single-phase winding cannot create a rotating field, additional means are needed to start the motor. Starting winding with capacitor creates phase shift that allows initial rotor motion. After starting, the motor can continue to run with the main winding only. Single-phase motors have lower efficiency and power than three-phase motors.

4.6.1 Speed Control

Classical speed control of asynchronous motors is possible by changing the supply frequency. Variable frequency drives, called frequency inverters or VFDs, convert fixed frequency and voltage from the grid to variable frequency and voltage. This allows smooth speed regulation from zero to rated speed and above. The inverter must maintain the appropriate ratio of voltage to frequency to preserve magnetic flux in the motor.

Modern frequency inverters use vector control or field-oriented control, which allows independent control of motor flux and torque. This significantly improves dynamic properties and allows accurate torque control even at low speeds. Vector control requires knowledge of motor parameters and often uses feedback from speed or position sensors, although sensorless variants are also available.

For applications not requiring continuous regulation, pole-count changing motors are available. These motors have specially designed winding that allows switching between different numbers of pole pairs, typically in ratio two to one. This allows step changing of synchronous speed, for example between fifteen hundred and three thousand revolutions per minute. Switching between speeds can be realized by mechanical contactors or semiconductor switches.

Energy recovery during braking is possible with bidirectional frequency inverters. During deceleration, the motor acts as a generator and converts mechanical energy back to electrical energy. This energy can be returned to the grid, which requires special inverter configuration, or can be dissipated in a braking resistor. Energy recovery is advantageous in applications with frequent braking, such as elevators or cranes.

The torque-speed characteristic of an asynchronous motor is descending – as speed increases, available torque decreases. Maximum torque, called breakdown torque, is typically two to three times the rated torque. Starting torque for standard squirrel cage motors is fifty to one hundred fifty percent of rated torque. Special high starting torque motors can achieve two hundred percent of rated torque.

Efficiency of modern asynchronous motors reaches ninety to ninety-six percent according to energy efficiency class. The highest efficiency class IE4 and IE5 represent premium efficiency motors used in the European Union and other regions with strict energy efficiency requirements. Higher efficiency means lower operating costs but higher acquisition cost. Return on investment depends on motor operating time and electricity price.

Power factor of asynchronous motors at rated load is typically zero point eight to zero point nine lagging. At partial load, the power factor decreases, which increases reactive current and losses in the distribution network. Power factor compensation using capacitors is common in industrial installations. Frequency inverters can improve power factor but can also generate harmonic distortion.

Reliability and lifespan of asynchronous motors are excellent. Typical lifespan is twenty to forty years with minimal maintenance. Main wearing parts are bearings, which must be periodically lubricated or replaced. Motors in harsh environments require protection class IP54 or higher and special treatment against corrosion and contamination.

Applications span all industrial sectors. Pumps and fans represent the largest application area, where energy savings through speed regulation are significant. Compressors and conveyor belts use asynchronous motors for continuous operation. Production machines, mixing equipment, and mills utilize their robustness and reliability. Household appliances including washing machines and refrigerators use single-phase asynchronous motors.

4.7 Synchronous AC motor

Synchronous electric motors (SD) are not as common as squirrel cage asynchronous motors. However, they are used where high torque is required and overloads often occur during operation. This type of motor is also used where high power is required to drive mechanisms, due to the high power factor and the ability to improve the power factor of the network, which will significantly reduce the cost of electricity and load on the line.

(principle of operation)

A synchronous motor is an electric motor in which the speed of rotation of the rotor (shaft) coincides with the speed of rotation of the stator magnetic field. The principle of operation of such an electric motor - is based on the interaction of a rotating stator magnetic field, which is usually formed by a three-phase alternating current and a constant magnetic field of the rotor.

The constant magnetic field of the rotor is formed by the excitation winding or permanent magnets. The current in the stator winding creates a rotating magnetic

field, while the rotor in the operating mode is a permanent magnet, its poles are thrown to the opposite poles of the stator magnetic field. As a result, the rotor rotates synchronously with the stator field, which is its main feature.
The speed of rotation of the stator magnetic field can be calculated using the following equation:

$$N = 60\frac{f}{p}$$

where:
f is the current frequency in the winding, Hz,
p is the number of pole pairs.
Accordingly, the speed of rotation of the synchronous motor shaft is determined according to the same formula.
Most AC electric motors used in production are manufactured without permanent magnets, but with an excitation winding, while low-power synchronous AC motors are manufactured with permanent magnets on the rotor.
Current is supplied to the field winding through slip rings and a brush assembly. Unlike a collector electric motor, where a collector (a group of longitudinally arranged plates) is used to transfer current to a rotating coil, the rings are mounted on a synchronous one across one end of the stator.
Thyristor exciters, often called, are currently a source of excitation by direct current. Previously, a generator-motor excitation system was used, when the generator was installed on the same shaft with the motor (it is also an exciter), which resistors applied current to the field winding.
One of the main characteristics of an electric motor is the mechanical characteristic. Synchronous motors have approached a straight horizontal line. This means that the load on the shaft will not affect its speed (until it reaches a critical value). This is achieved precisely due to direct current excitation, and therefore a synchronous electric motor perfectly maintains a constant speed with changing loads, overloads and voltage drops (up to a certain limit).
A feature of this type of electrical machines is that they cannot simply be connected to the network and wait for it to start. In addition, for operation, not only a source of excitation current is required, but also a rather complicated starting circuit. Starting occurs in the same way as in an induction motor, and to create a starting torque, in addition to the field winding, an additional “damping” winding is placed on the rotor, which increases stability during sudden overloads. There is no excitation current in the rotor winding at start-up, and when it accelerates to subsynchronous speeds (3-5% less than synchronous), an excitation current is applied, after which it oscillates and the stator current the motor enters synchronization and goes into operating mode.
To limit the starting currents of powerful machines, they sometimes reduce the voltage at the terminals of the stator windings by connecting a series autotransformer or resistors.

While the synchronous machine is starting in asynchronous mode, resistors are connected to the field winding, the resistance of which is 5-10 times greater than the resistance of the winding itself. This is necessary so that the pulsating magnetic flux arising from the action of currents induced in the winding during start-up does not slow down acceleration, and also so that the windings are not damaged due to the electromagnetic field induced in it.

Synchronous motors are more expensive than asynchronous ones, in addition, they require an additional source of direct current excitation - this partially reduces the breadth of the range of this type of electrical machines. However, synchronous electric motors are used to drive mechanisms where overloads are possible and precise maintenance of stable speeds is required.

In addition, they are most often used in the area of u200b\u200bhigh power - hundreds of kilowatts and units of megawatts, and at the same time, starting and stopping are quite rare, that is, the machines operate 24 hours a day. This application is due to the fact that synchronous machines operate with cos φ close to 1. The maximum torque developed on the shaft is proportional to U and for AD - U^2 (quadratic dependence on voltage). This means that it has good load capacity and stability, which are maintained when the voltage drops in the network. As a result, the rotation speed is stable during overload and underload, within the overload capacity, especially with increasing excitation current.

However, a significant disadvantage of the synchronous motor is its design is more complex than that of an asynchronous one, it requires an exciter without which it cannot work. All this leads to higher costs compared to asynchronous machines and difficulties in maintenance and operation.

4.8 Frequency converters and AC motor control

A frequency converter (Fig. 33), in English terminology referred to as a VFD for Variable Frequency Drive or inverter, is an electronic device that enables continuous speed control of asynchronous motors by changing the frequency and amplitude of the supply voltage.

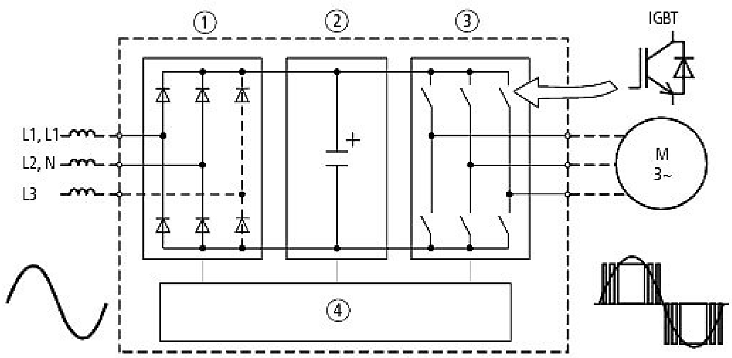

Fig. 33 Frequency converter

The development of power semiconductor technology has enabled the mass deployment of frequency converters across all industries in recent decades, which has led to a significant increase in energy efficiency and flexibility of production processes. Frequency converters have become a standard solution wherever it is necessary to control the speed of a motor.The basic design of a frequency converter consists of three main parts. The rectifier converts the alternating voltage from the mains to direct current. The most commonly used is a three-phase bridge rectifier with diodes, which produces a pulsating direct current. The intermediate circuit, also known as the DC link, contains capacitors that smooth out the pulsating voltage from the rectifier and create a stable DC voltage source for the next section. The inverter, also called the inverter, converts the DC voltage back into a three-phase AC voltage with adjustable frequency and amplitude. The inverter uses six power transistors, typically IGBTs, connected in a three-phase bridge.
(principle of operation)
(use of a frequency converter)
The generation of the AC voltage in the inverter is realized using pulse-width modulation. Each phase of the output voltage is generated by rapidly switching the corresponding pair of transistors between the positive and negative poles of the DC voltage. The switching frequency is typically several kilohertz. The average value of the output voltage is determined by the ratio of the time during which the phase is connected to the positive pole to the time it is connected to the negative pole. By changing this ratio during one period of the output frequency, a sinusoidal waveform of the average voltage value is created. The motor, which is inductive in nature, filters out the high-frequency components and perceives only the average value corresponding to the desired sinusoid.
Scalar control, also known as V/f control, is the simplest and most widespread method of controlling asynchronous motors using a frequency converter. The principle of scalar control consists in maintaining a constant ratio between the output voltage and the frequency. This ratio ensures that the magnetic flux in the motor remains approximately constant regardless of the speed. At a nominal frequency of fifty hertz, the output voltage is full, for example, four hundred volts. At a half frequency of twenty-five hertz, the voltage is reduced by half, two hundred volts. At low frequencies below five hertz, voltage compensation is often applied, because the resistive voltage drop across the motor winding becomes significant.
Vector control, also known as FOC for Field Oriented Control, is an advanced control method that provides properties comparable to DC motors. Vector control uses mathematical transformations to decompose the stator current into two components in a rotating coordinate system linked to the rotor magnetic field. One component determines the magnetic flux, the other component determines the torque. These two components can be controlled independently, which allows for precise and dynamic torque control independent of speed. Vector control requires knowledge of the rotor position, which is obtained either from an encoder or estimated from input variables.

The dynamics of a vector-controlled asynchronous motor are comparable to servo drives.
Modern frequency converters include a wide range of protection functions and diagnostic tools. Overload protection monitors the motor current and, if the rated value is exceeded for a permitted time, the converter declares a fault and disconnects the motor. Short-circuit protection detects excessive current and immediately switches off the output. Undervoltage and overvoltage protection on the input and in the intermediate circuit. Thermal protection monitors the temperature of the power elements and reduces the power or stops operation in case of overheating. Phase failure protection detects a missing phase at the input or output. Diagnostics allows monitoring of operating parameters, error history and operating hours.
Communication interfaces of modern frequency converters enable integration into automation systems. Analog inputs allow setting the desired speed with a voltage or current signal. Digital inputs are used for basic commands such as start, stop and error reset. Industrial buses such as Modbus RTU, Profibus, DeviceNet or EtherNet/IP enable complex parameterization, control and diagnostics. USB or Ethernet interface allows connection of a laptop for setting and monitoring.
The advantages of using a frequency converter include primarily energy savings, which can reach thirty to fifty percent in applications such as pumps and fans. Smooth start-up reduces mechanical stress and eliminates current surges. Possibility of precise speed and torque control for process optimization. Protective functions extend the service lifemotor. Possibility to brake the motor and regenerate energy back into the grid. Noise reduction at lower speeds. Elimination of mechanical elements for speed control such as pulleys and gearboxes.
The disadvantages and limitations of frequency converters lie in the investment costs, which can be significant for smaller motors. The generation of electromagnetic interference requires shielded cables and filters. Higher harmonic current components taken from the grid may require filtering. Increased stress on the motor insulation by high-frequency voltage pulses can shorten the life of older motors not designed for operation with a converter. The need for protective circuits for long cables between the converter and the motor.

4.9 Motor Selection and Sizing

Selecting the right electric motor for a specific application is a complex process that requires analysis of multiple factors and understanding of the application requirements. Incorrect motor selection can lead to insufficient performance, reduced service life, excessive wear of mechanical components, or unnecessarily high costs. A systematic approach to motor selection includes determining the requirements, analyzing the load, calculating the required power and torque, selecting the motor type, and verifying that all criteria are met.
The first step is to determine the application requirements. The type of motion needs to be defined, whether it is rotary or linear, continuous or intermittent, constant or variable speed. The required speed determines the motor speed, and consideration

must be given to whether a gear mechanism will be required. The path and positioning accuracy determine whether a stepper motor is sufficient or a servo system is required. Dynamic requirements such as acceleration and deceleration times affect the selection of the motor type and the required power. The operating environment determines the motor IP rating and ambient temperature.

Load analysis is key to the correct dimensioning of the motor. The load torque can have different characteristics depending on the application. A constant torque occurs, for example, when lifting a load or in conveyors. A torque that increases linearly with speed occurs in positive displacement pumps. A torque that increases quadratically with speed is typical for fans and pumps. The load torque must be determined for various operating conditions, including starting, steady-state operation, and braking. In cyclic operation, load cycles and downtimes must be considered.

The calculation of the required torque is based on the mechanics of the application. For rotary motion, the basic relationship is that torque equals the load torque plus the torque required to accelerate the inertial mass. The torque required for acceleration depends on the total inertia of the system including the motor rotor, coupling, gearbox, and load. For linear motion, the weight of the load being moved, friction forces, and possibly the gravitational force during the stroke must be considered. When using a gear mechanism, the torques are converted through the gear ratio and the efficiency of the gearbox must be taken into account.

The motor power is determined from the relationship power equals torque times angular velocity divided by the efficiency of the entire drive chain. It is important to consider that with a variable load, the effective value of the torque is used instead of the maximum torque. In cyclic operation, it is necessary to calculate the effective torque from the load cycle. The motor must be able to provide the peak torque required for a short time during start-up or during transient events. The safety margin in power should be twenty to fifty percent depending on the accuracy of the load determination and the dynamic requirements.

The choice of motor type depends on the specific requirements of the application. Brushed DC motors are suitable for simple applications with low costs where there are no critical requirements for life and maintenance. BLDC motors are suitable for applications requiring high power in a small size, long life and high efficiency. Stepper motors are suitable for applications requiring positioning without feedback, low to medium speeds and medium accuracy. Servomotors are suitable for applications requiring high dynamics, precision and complex motion profiles. AC asynchronous motors with frequency converters are suitable for higher powers, continuous operation and simple speed control.

Other factors influencing the selection include the supply voltage, which must match the available source. The mounting dimensions and weight of the motor must be compatible with the mechanical design. The type of shaft, whether it is a plain shaft with a key or a hollow shaft. The type of flange for mounting on the machine. The cooling requirements determine whether natural cooling is sufficient or forced cooling is necessary. Life and reliability are critical for applications where motor replacement is expensive. The costs include not only the purchase price but also the operating costs for energy and maintenance.

Manufacturers' catalog data provide the necessary information to verify the correctness of the selection. Torque curves show the dependence of the available torque on speed, while it is necessary to verify that the motor provides sufficient torque over the entire operating speed range. Duty cycles indicate how long the motor can operate at various loads without overheating. Thermal time constants determine how quickly the motor heats up and cools down, which is important for cyclic modes. Mechanical time constants determine how quickly the motor can accelerate. The operating temperature range defines the climatic conditions for operation. Information on noise, vibration and electromagnetic compatibility is important for some applications.

Verification of the correct selection should include checking that the maximum motor torque at operating speed is higher than the required load torque with a safety margin. The peak motor torque must be sufficient for starting and transientse. The thermal load of the motor at the expected load cycle must be within the rated values. The mechanical stress of the shaft and bearings must be within the permitted values. The electrical parameters such as voltage, current and frequency range must be compatible with the control electronics used. The motor life must correspond to the requirements of the application.

5 PNEUMATIC SYSTEMS

Pneumatic systems are one of the most widely used automation technologies in modern industry. They use compressed air as a working medium for energy transfer and motion control, providing safe, environmentally friendly, and cost-effective solutions for a wide range of applications. From packaging lines to assembly stations to bus door mechanisms, pneumatics is a ubiquitous technology that forms the basis of many mechatronic systems.

The history of pneumatics dates back to ancient times, when air was used for glass blowing and bellows in metallurgy. The modern era of pneumatics began in the nineteenth century with the invention of efficient compressors and the advances of the Industrial Revolution. Today, pneumatic systems are used in automotive manufacturing, food production, the pharmaceutical industry, packaging and transport systems, as well as in construction and mining.

A key feature of pneumatic systems is the use of air as the working medium. Air is freely available in the atmosphere, non-flammable, clean, and does not contaminate the environment or products in the event of leakage. These properties make pneumatic systems an ideal choice for applications with strict requirements for safety, cleanliness, or fire protection. On the other hand, the compressibility of air limits positioning accuracy and the overall energy efficiency of the system, which must be taken into account when designing mechatronic applications.

5.1 Pneumatics – basic principles and properties

Pneumatics is a field of technology concerned with the use of compressed air to transfer energy, perform mechanical work, and control motion. The basis of pneumatic systems lies in the ability of air to be compressed, store energy in its compressed state, and then release this energy during expansion. This property makes it possible to convert mechanical energy from a compressor into the potential energy of compressed air, which can be stored, distributed, and later used to drive actuators in various parts of an industrial plant.

The physical behavior of air in pneumatic systems is described by basic gas laws, which were discovered empirically as early as the seventeenth and eighteenth centuries. Boyle's law describes the relationship between the pressure and volume of a gas at constant temperature. For an isothermal process, the following applies:

$$pV = constant$$

where:
p is the absolute pressure of the gas measured in pascals,
V is the volume of the gas in cubic meters.
For two different states of the same amount of gas at a constant temperature, we can write:

$$p_1V_1 = p_2V_2$$

This relationship is fundamental to understanding air compression in compressors and its subsequent expansion in pneumatic actuators. When pressure is doubled, the

volume of the gas is halved, which explains why compressed air contains a significant amount of stored energy.
Charles's law describes the relationship between the volume and temperature of a gas at constant pressure. In an isobaric process, the volume of a gas is directly proportional to its absolute temperature. Gay-Lussac's law describes the relationship between pressure and temperature at constant volume – the pressure of a gas in a closed container increases with temperature [Fig. 34].
These three laws can be combined into the general ideal gas law:

$$pV = nRT$$

where:
n is the amount of gas in moles,
R is the universal gas constant with a value of 8,314 J/(mol·K),
T is the absolute temperature in kelvins.
For technical calculations in pneumatics, the form of the law with gas mass is often used:

$$pV = mrT$$

where:
m is the mass of gas in kilograms,
r is the specific gas constant for air, with a value of approximately 287 J/(kg·K).

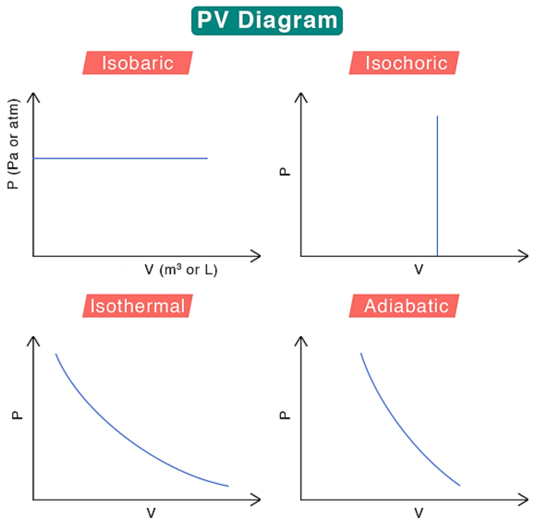

Fig. 34 Diagram p - V for different cases

The compressibility of air is a key property that influences the behavior of pneumatic systems. Unlike the fluids used in hydraulics, air can be compressed significantly—at a pressure of 6 bar (6 atm, 0,6 MPa), the volume of air is reduced to approximately one-sixth of its original value. This compressibility has important consequences for the dynamic behavior of pneumatic systems. Compressed air in actuators acts like a spring, resulting in elastic behavior of the entire system. Movements are softer and more compliant compared to hydraulics, where the working fluid is practically incompressible.

Air compression causes a significant increase in temperature, which results from the conversion of the mechanical work of the compressor into the internal energy of the gas. For adiabatic compression, where no heat is exchanged with the environment, Poisson's equation applies:

$$p_1 V_1^\kappa = p_2 V_2^\kappa$$

where:

κ is Poisson's constant for air, with a value of approximately 1,4.

Adiabatic compression leads to significant heating of the air – when the pressure is increased from atmospheric pressure to 6 bar, the temperature can rise by more than 150°C. Therefore, it is necessary to cool the air after compression and remove the condensed moisture.

The typical working pressure in industrial pneumatic systems is 6 bar (600 kPa or 0.6 MPa), which corresponds to a ratio between relative and absolute pressure of approximately seven (atmospheric pressure being about 1 bar). This value represents a compromise between several factors. At higher pressures, actuator force increases and smaller cylinder diameters can be used, but energy consumption for compression, sealing requirements, leakage risk, and exhaust noise levels all increase. Lower pressures would require larger actuators and result in slower movements. Some applications use reduced pressures of around 4 bar for simpler tasks, while others use higher pressures of up to 10 bar for more demanding applications requiring greater forces.

Air density depends on pressure and temperature according to the equation of state. At atmospheric pressure and a temperature of 20°C, the density of air is approximately 1,2 kg/m^3. When compressed to 6 bar, the density increases by roughly a factor of seven, to about 7,2 kg/m^3. This change in density is of practical importance when dimensioning storage tanks and calculating the amount of energy stored in compressed air. However, the energy density of compressed air is relatively low compared to hydraulic systems or electric batteries, which is one of the disadvantages of pneumatics.

The properties of air as a working medium also influence the maximum achievable forces and speeds of pneumatic actuators. The force of a pneumatic cylinder is given by the simple equation:

$$F = pA$$

where:

F is the force in newtons, p is the working pressure in pascals,

A is the effective piston area in square meters.

At a typical pressure of 6 bar and a cylinder diameter of 50 mm, the theoretical force is approximately 1180 N. In practice, the actual force is slightly lower due to seal friction and system losses. To increase the force, it is necessary to either enlarge the cylinder diameter or use a higher pressure, both of which have their limitations and disadvantages.

The speed of movement of a pneumatic cylinder piston depends on the air flow rate and the cylinder diameter. In typical industrial applications, pneumatic cylinders

achieve speeds in the range of 0.1 to 2 m/s. Higher speeds are possible with smaller cylinders and higher flow rates, but they lead to issues such as noise, impact at end positions, and increased wear. Conversely, very low speeds below 10 mm/s are problematic due to the stick–slip effect, where the cylinder moves in jerks rather than smoothly because of the difference between static and dynamic friction.
The thermal properties of air play an important role in the behavior of pneumatic systems. The specific heat capacity of air at constant pressure is approximately 1000 J/(kg·K), which is a relatively high value that allows air to absorb a significant amount of heat with only a small change in temperature. The rapid expansion of air in a pneumatic cylinder causes cooling, which in extreme conditions can lead to the freezing of condensed moisture and the blockage of valves. Therefore, it is important to properly treat and dry the air before it enters the pneumatic system.
The relationship between air flow and piston speed is determined by the continuity equation:

$$Q = Av$$

where:
Q is the volume flow rate in cubic meters per second,
A is the cross-sectional area of the cylinder,
v is the piston speed in meters per second.
To achieve higher speeds, sufficient air flow must be ensured, which requires valves with larger cross-sections and pipes with sufficient diameter. An undersized air supply limits the maximum speed of the cylinder regardless of the available pressure.
Basic thermodynamic laws of gases:

$$\frac{pV}{T} = const$$

Boyle-Marriott's Law

$$T = const; p \cdot V = const$$

Gay-Lussac's law

$$p = const; \quad V/T = const$$

Charles-Gay-Lussac's law

$$V = const; \quad \frac{p}{T} = const$$

The properties of air as a working medium determine not only the performance characteristics of pneumatic systems, but also the types of applications in which they are most suitable. Pneumatics are ideal for tasks requiring fast, simple movements with relatively low forces, where strict positioning accuracy is not critical. Typical applications include gripping and moving parts on assembly lines, controlling gates and doors, packaging products, pushing materials, and performing simple handling operations. Conversely, hydraulic or electric drives are better suited for applications that demand high forces, precise position control, or continuous motion at variable speeds.

Tab. 4 Comparison of basic characteristics of pneumatics and hydraulics

Parameter	Pneumatics	Hydraulics
Working medium	Compressed air	Hydraulic oil
Compressibility	High (compressible gas)	Virtually zero
Typical working pressure	6 bar (600 kPa)	100-350 bar (10-35 MPa)
Maximum force (cylinder Ø50mm)	1200 N	40000 N
Typical cylinder speed	0,1 - 2 m/s	0,05 – 0,5 m/s
Positioning accuracy	Low (±1-5 mm)	High (±0.01-0.1 mm)
Energy efficiency	20-30%	40-60%
Safety	High (non-flammable)	Medium (flammable oils)
Cleanliness in case of leakage	Clean (no contamination)	Environmental contamination
System costs	Lower	Higher
Noise level	High (air exhaust)	Lower

5.2 Advantages and disadvantages of pneumatic systems

Pneumatic systems possess a distinct set of characteristics that make them well-suited for certain applications, while rendering them less suitable for others. Understanding these advantages and disadvantages is essential for making informed decisions when designing mechatronic systems and selecting the optimal type of drive.

The primary advantage of pneumatics is operational safety. Air, as a working medium, is non-flammable and non-explosive, making pneumatic systems safe to use in environments with a risk of fire or explosion. In the chemical industry, refineries, paint shops, facilities for storing flammable substances, or mining operations where flammable dust, gases, or vapors are present, pneumatic systems are often the only acceptable option. If a pneumatic system fails, it does not produce sparks or cause explosions, which significantly reduces risks to personnel and equipment. In contrast, hydraulic systems containing flammable oil or electric drives that may spark pose a considerable risk in such environments.

Clean operation is another significant advantage of pneumatics. When compressed air leaks from a pneumatic system, only air is released into the atmosphere, without contaminating products, the working environment, or the surroundings. This feature makes pneumatic systems ideal for the food industry, pharmaceutical industry, semiconductor manufacturing, and other applications where cleanliness is critical. Typical examples include bottling lines, bottle filling and capping equipment, cleanroom manipulators, and sterile product packaging. In contrast, hydraulic systems pose a risk of product contamination if oil leaks from seals.

The simplicity of design and operation of pneumatic components also contributes to their widespread use. Pneumatic cylinders, valves, and auxiliary components generally have a simple design with fewer precision parts compared to hydraulics. This leads to lower manufacturing costs and easier system assembly and installation. Pneumatic components are available in standardized designs from many manufacturers, which reduces costs and shortens delivery times. Furthermore, pneumatic systems do not require a return line for the working medium, as air is simply vented to the atmosphere, unlike hydraulic systems.

Maintenance of pneumatic systems is relatively undemanding. Components have a long service life and require only minimal regular maintenance. The main maintenance tasks include checking and replacing filters in the FRL unit, draining condensate, inspecting seals, and occasionally lubricating moving parts. Unlike hydraulic systems, there is no need to regularly analyze or replace the working fluid, monitor its viscosity, contamination, or degree of degradation. Pneumatic components are typically robust and resistant to mechanical stress. In the event of a failure, replacement parts are readily available, and repairs can be carried out quickly and easily.

The speed of movement is one of the characteristic advantages of pneumatics. Air compresses and expands rapidly, enabling very fast actuator cycles. Pneumatic cylinders typically achieve speeds of 0,5 to 1,5 m/s, with speeds exceeding 2 m/s in specialized applications. The response time of pneumatic systems is on the order of milliseconds, allowing high-frequency cyclic movements. This feature makes pneumatics ideal for pick-and-place operations on assembly lines, rapid product packaging, sorting, and parts handling in automated manufacturing systems. Hydraulic systems are generally slower due to the higher density and viscosity of the working fluid.

Resistance to overload is a natural property of pneumatic systems resulting from the compressibility of air. When the cylinder piston hits an obstacle or reaches its end position, the air is simply compressed and the pressure increases to the safety limit set by the pressure reducer. There is no mechanical damage to the cylinder, valve, or other components. The air acts as a spring buffer, absorbing shocks and vibrations. This property is advantageous in applications where unexpected obstacles or collisions may occur. Hydraulic and electric drives are more sensitive to overload and require special protective mechanisms.

The availability of the working medium is a practical advantage of pneumatics. Air is freely available in the atmosphere and does not require purchase, transport, or storage like hydraulic oil. All you need to invest in is a compressor and an air preparation system that can serve the entire plant. There are no costs for the regular purchase of working fluid or its disposal at the end of its service life. In the event of an air leak, there is no need to replenish the expensive medium – the compressor automatically replenishes the missing amount from the air in the atmosphere..

Despite their many advantages, pneumatic systems also have significant disadvantages that limit their use in certain applications. The most serious drawback is the low overall energy efficiency of the system. The total efficiency, from the electrical energy input to the compressor to the mechanical work output at the cylinder, is typically only 20 to 30 percent. Several factors contribute to this. The compression of air in the compressor itself is energy-intensive, with an efficiency of 60 to 80 percent. A significant portion of the energy is converted into heat, which must be removed by cooling. Further losses occur during air distribution through the piping system – friction of air against the pipe walls, turbulent flow, and leaks through imperfect seals. When air is exhausted into the atmosphere, its remaining energy is wasted.

Numerous studies have analyzed energy losses in pneumatic systems. Analyses show that in industrial plants, up to 30% of the electrical energy used to produce compressed air can be lost through leaks before performing any useful work. An additional 10% to 20% is lost due to oversized components, excessive pressure, or incorrect system settings. Modern approaches to optimizing pneumatic systems focus on detecting and repairing leaks, reducing operating pressure to the minimum necessary for a given application, using more efficient compressors, and recovering heat from compression.

The limited force of pneumatic actuators is another significant disadvantage. At a typical working pressure of 6 bar and common cylinder diameters (25 to 100 mm), forces ranging from several hundred to several thousand newtons can be achieved. For applications requiring greater forces, large-diameter cylinders must be used, resulting in disproportionate actuator size and weight. In contrast, hydraulic systems operating at pressures of 100 to 350 bar can generate forces ten to fifty times higher with the same cylinder dimensions. Therefore, pneumatic systems are primarily suitable for light handling tasks, while heavy-duty applications such as pressing, lifting heavy loads, or controlling construction machinery require hydraulic drives.

Limited positioning accuracy is a direct consequence of the compressibility of air. Compressed air in a pneumatic cylinder acts like a spring, deforming under load. When the load changes, the piston position also changes. This behavior makes precise positioning impossible without feedback and control. The typical accuracy of an uncontrolled pneumatic system ranges from millimeters to centimeters, which is insufficient for many applications. Hydraulic systems, using an almost incompressible medium, can achieve positioning repeatability within hundredths of a millimeter. For tasks requiring precise position control, either servo-controlled pneumatic systems with proportional valves and position sensors are used, or electric or hydraulic drives are preferred.

The significant noise level of pneumatic systems is often underestimated, yet it represents a practically important disadvantage. When compressed air is released from a pneumatic cylinder or valve into the atmosphere, it expands rapidly, generating noise levels that frequently exceed 80 to 90 dB(A), necessitating the use of personal protective equipment. In modern production halls with numerous pneumatic systems, the overall noise level can substantially exceed permissible limits for the working environment. Noise dampers (silencers) fitted to valve and cylinder exhausts, containing porous materials that slow air expansion, can reduce noise by 20 to 40 dB. Even with such dampers, however, pneumatic systems remain noisier than hydraulic or electric drives.

The need for high-quality compressed air preparation introduces additional costs and maintenance requirements. Air from the compressor contains moisture, oil from the compressor, and solid contaminants. Moisture condenses when cooled, potentially causing valve freezing, corrosion of internal surfaces, and deterioration of lubricating properties. Solid contaminants contribute to wear on seals and precision surfaces. To ensure reliable operation of a pneumatic system, the air must be properly dried and

filtered, and, in some cases, lubricated with a fine oil mist. This requires the installation of an FRL unit (filter, regulator, lubricator), with ongoing costs for replacing filter cartridges, draining condensate, and replenishing lubricating oil.
The issue of moisture condensation in pneumatic systems requires special attention. Atmospheric air contains water vapor in amounts that depend on temperature and relative humidity. Compression significantly increases the concentration of water vapor, and subsequent cooling of the compressed air in pipes and components causes condensation. A single compressor with a capacity of 10 m^3/min can produce tens of liters of condensate per day. This water must be removed to prevent problems in the system. The solution is to use air dryers, which reduce the dew point below the operating temperature of the system.
Compromises in pneumatic system design are inevitable. Higher working pressure provides greater forces for the same cylinder diameter, but also increases energy consumption for compression, exhaust noise, and sealing requirements. Larger cylinder diameters allow for higher forces, but result in increased dimensions, weight, and air consumption. Faster movements require higher air flow rates, which necessitates larger pipe diameters, more expensive valves with larger cross-sections, and higher noise levels. Each application requires careful consideration to find the optimal solution that balances the advantages and disadvantages of pneumatics.

5.3 Compressed air preparation – compressor and distribution

High-quality preparation and distribution of compressed air are essential for the reliable operation of pneumatic systems. This process begins with the intake of atmospheric air, continues with compression to the required pressure, air quality treatment, and ends with distribution through the piping system to the end-use devices. Each of these stages is important and requires proper design and maintenance.
The compressor is the energy center of a pneumatic system, converting mechanical energy from an electric motor into the potential energy of compressed air. There are several types of compressors that differ in operating principles, performance characteristics, and areas of application. The choice of a suitable compressor type depends on the required capacity, pressure, air quality, operating mode, and economic factors.
Piston compressors (Fig. 35), are among the oldest and most widely used types of compressors.

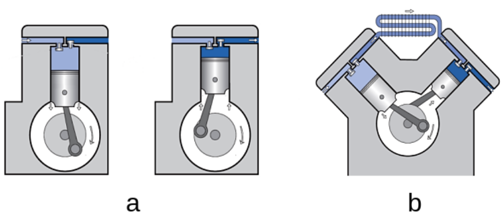

Fig. 35 Piston compressors
a – single-stage, b – two-stage

Their operating principle is similar to that of an internal combustion engine: the piston performs a reciprocating motion in the cylinder, drawing atmospheric air through intake valves during the suction stroke, compressing it during the compression stroke, and releasing the compressed air through discharge valves into a storage tank when the required pressure is reached. Piston compressors can be single-stage or multi-stage. In single-stage compression, the air is compressed to the final pressure in one step, which is suitable for pressures up to 10 bar.

For higher pressures, multi-stage compression is used, where the air is gradually compressed in several stages with intermediate cooling, which reduces the final temperature and increases the efficiency of the process.

The advantages of piston compressors include a relatively low purchase price, simple design, the ability to achieve high pressures, and suitability for intermittent operation. Their disadvantages include significant pressure pulsations, which require a large reservoir, higher noise levels caused by dynamic forces, more frequent maintenance due to wear on piston rings and valves, and relatively low efficiency at lower outputs. Piston compressors are primarily used in small – and medium-sized operations, workshops, service centers, and mobile applications, where their robustness and ability to operate under harsh conditions are beneficial.

Screw compressors (Fig. 36) provide a modern and efficient method of producing compressed air for industrial applications. Air compression is achieved by two intermeshing helical rotors – one typically with four lobes and the other with six grooves. As the shafts rotate, air trapped in the spaces between the lobes is gradually compressed towards the outlet. The process is continuous, without pulsation, resulting in quieter operation and more stable pressure.

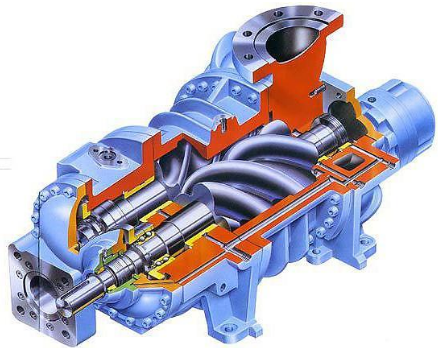

Fig. 36 Screw compressor

The advantages of screw compressors include high volumetric efficiency, typically between 85% and 95%, low noise levels due to the absence of valves and balanced rotating masses, the capability for continuous operation without interruption, long maintenance intervals, and stable pressure without pulsations. Disadvantages include a higher purchase price, the need for qualified maintenance personnel, and sensitivity to the quality of the intake air. Screw compressors dominate industrial central compressor stations, providing compressed air for entire production plants. Their power range extends from a few kilowatts to several megawatts of installed capacity.

(principle of operation), (principle of operation)
Diaphragm compressors (Fig. 37) use an elastic diaphragm that periodically flexes to compress air within the compression chamber.

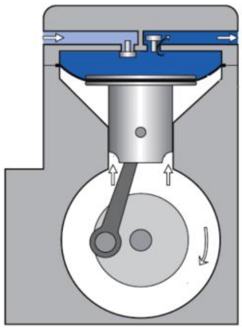

Fig. 37 Diaphragm compressors

The diaphragm is actuated by an eccentric mechanism or an electromagnet. The primary advantage of diaphragm compressors is the production of oil-free, completely clean compressed air, since the air does not come into contact with any lubricated parts. Diaphragm compressors are widely used in medical applications, laboratories, the pharmaceutical industry, and any situation where air purity is critical. Their main disadvantages are low output and the inability to achieve high pressures.
Rotary vane compressors (Fig. 38) have a rotor with radial slots that house movable vanes. During rotation, the vanes are pushed outward by centrifugal force and slide along the inner surface of the stator, which is eccentric relative to the rotor axis. Chambers of varying size are formed between the individual vanes, resulting in air compression. Vane compressors provide a compromise between piston and screw compressors: they are quieter than piston compressors, less expensive than screw compressors, but have lower efficiency and experience higher vane wear.

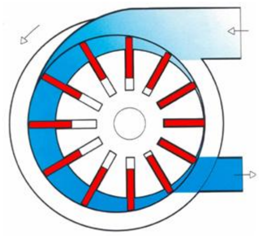

Fig. 38 Rotary vane compressors

In addition to the compressor itself, a compressor station (Fig. 39) also includes other components that ensure the proper functioning of the system. An air cooler is necessary to reduce the temperature of the air after compression. During adiabatic compression to 6 bar, the air temperature can rise above 150°C, which is unacceptable for pneumatic components. The cooler is typically an air-to-air heat exchanger with fans or a water cooler connected to a cooling circuit. Cooling the air also condenses a significant portion of the moisture, which is removed through a condensate separator.

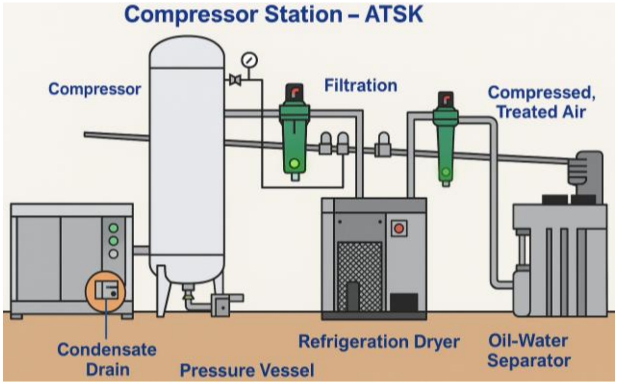

Fig. 39 Compressor station diagram

The receiver is a pressure vessel that serves as a buffer for the pneumatic system. It performs multiple functions: it dampens pressure pulsations caused by the intermittent operation of piston compressors or fluctuating air consumption in the system; allows the compressor to operate in its optimal mode with longer periods of operation and rest, controlled by a pressure switch; stores energy to cover short-term consumption peaks; and provides additional cooling and condensate separation. The volume of the storage tank is determined based on the compressor's performance, the nature of consumption, and the required frequency of compressor switching. Typical capacities range from 100 to 500 liters for smaller systems and several cubic meters for industrial plants.

The compressed air distribution network transports air from the storage tank to the end users. The design of the distribution network is critical for the energy efficiency of the system. The main pipe has a larger diameter and is connected to side branches serving individual workstations. Important design principles include using pipes with sufficient diameter to minimize pressure losses, maintaining horizontal sections with a slight slope toward condensate drains, installing shut-off valves on main branches to allow maintenance, using flexible hoses for moving equipment, and minimizing the number of elbows and joints. Pipes can be made of steel, aluminum, or plastic, with each material offering its own advantages and disadvantages.

Pipe dimensioning represents a compromise between minimizing pressure losses and controlling costs. As air flows through a pipe, pressure drops occur due to friction against the pipe walls and turbulence. These losses depend on the pipe diameter, length, inner surface roughness, flow velocity, and air viscosity. To minimize losses, sufficiently large pipe diameters should be used; however, excessively large pipes unnecessarily increase costs. Recommended air velocities are 6 to 10 m/s in the main distribution lines and up to 15 m/s in the side branches. Manufacturers of pneumatic components provide tables and charts for pipe sizing based on air flow and allowable pressure drop.

Condensate management in the distribution network requires a systematic approach. Horizontal pipe sections are designed with a slight slope (0,5-1%) in the direction of airflow. Automatic condensate drains are installed at the lowest points to remove accumulated moisture. Vertically rising pipes draw air from above so that condensate flows downward and is not carried along with the airflow. The pipe material should be resistant to corrosion, as moist air can lead to internal corrosion, which contributes to system contamination.

Tab. 5 Comparison of compressor types for pneumatic systems

Parameter	Piston	Screw	Diaphragm	Rotary vane
Principle of operation	Piston reciprocating motion	Rotating screws	Flexible membrane	Rotating vanes
Typical performance	0,5 - 30 kW	5 - 500 kW	0.1 - 3 kW	3 - 75 kW
Max. pressure	10 - 40 bar	7 - 13 bar	2 - 8 bar	7 - 10 bar
Volume efficiency	65 - 80%	85 – 95%	50 – 70%	70 – 85%
Noise level	High (85-95 dB)	Medium (65-75 dB)	Low (50-60 dB)	Medium (70-80 dB)
Air quality	Oil in air	Oil in air	Oil-free	Oil in air
Operating mode	Intermittent	Continuous	Intermittent	Continuous
Maintenance (interval)	Demanding (500-1000 h)	Low (3000-6000 h)	Minimal	Medium (1500-3000 h)
Purchase	Low	High	Medium	Medium
Typical use	Workshops, service centers	Industry,	Medicine, laboratories	Medium operations

Note: Values are approximate and depend on the specific type and size of the compressor

Modern central compressor stations use control systems that optimize energy consumption. When multiple compressors are operating in parallel, their operation is coordinated to make the overall system as efficient as possible. Smaller compressors cover basic consumption, while larger ones are connected during peak periods. Frequency converters enable smooth regulation of compressor speeds and adjustment of performance to current consumption. Leak monitoring and regular audits help identify and eliminate losses in the system.

5.4 FRL unit – filtration, regulation, lubrication

The air filter is the first element in the FRL unit chain and is designed to remove solid contaminants and liquid condensate from the compressed air. These contaminants originate from several sources. Atmospheric air drawn in by the compressor contains dust, pollen, and other solid particles. During compression, oil and water from the compressor, as well as rust and scale from the piping, may also enter the airflow. The filter traps these particles and separates condensate, preventing them from reaching downstream components and causing wear or blockages.

The regulator, the second component of the FRL unit, maintains the pneumatic system at a stable working pressure. It adjusts the pressure to the required setpoint for the actuators and valves, ensuring consistent performance. By preventing overpressure, the regulator protects equipment from damage and extends the service life of the system.

The lubricator, the final element, adds a controlled amount of oil mist to the compressed air. This reduces friction and wear in moving parts such as cylinder seals, valve spools, and pneumatic motors. While not all systems require lubrication – especially those using pre-lubricated or self-lubricating components – many industrial applications benefit from this step, particularly in high-speed or heavily loaded systems.

Proper selection, installation, and maintenance of the FRL unit are essential for ensuring reliable, long-term operation of pneumatic systems. Regular inspection, filter replacement, condensate draining, and oil replenishment are necessary to keep the system functioning optimally.

The design of the air filter is based on a two-stage separation principle. In the first stage, a centrifugal separator is used: air enters the cylindrical chamber tangentially, and the resulting forced rotation causes heavier particles and liquid droplets to be flung to the chamber walls. The separated contaminants then flow down into a collection container.

The second stage consists of a fine filter insert made of porous material, such as reinforced cellulose, ceramics, or synthetic fibers, which captures fine solid particles. The filtration efficiency is indicated by the size of the retained particles, typically 5, 25, or 40 μm (microns). For standard industrial applications, 40 μm filtration is usually sufficient, while sensitive applications – such as pneumatic metrology or precision component control – require finer filters with a filtration rating of 5 μm or even 1 μm.

An important feature of the filter is the transparent collection container equipped with a condensate drain. The container allows visual inspection of the accumulated condensate. The drain can be either manual (screw valve) or automatic (float valve). Automatic drains are preferred in industrial environments because they eliminate human error and ensure continuous condensate removal. If the container becomes full, condensate can leak back into the system, compromising filtration efficiency.

The filter cartridge should be checked and replaced regularly, typically every 2,000 to 4,000 operating hours, depending on the level of air contamination. Proper maintenance ensures consistent system performance and prevents premature wear of downstream pneumatic components.

The pressure regulator (also called a reducer or reduction valve) is the second component of the FRL unit and ensures a constant outlet pressure regardless of fluctuations in inlet pressure or flow. In a compressed air distribution network, pressure can vary due to compressor start-ups and shutdowns, changes in consumption in other parts of the system, or pressure losses during sudden consumption peaks. Pneumatic components, however, are designed to operate at a specific nominal pressure, typically 6 bar. Operating at lower pressures leads to insufficient force and slower movement, while higher pressures increase wear, air consumption, and can damage sensitive components.

The pressure regulator operates on the principle of force balance on a diaphragm or piston. The outlet pressure acts on one side of the diaphragm, while the force of an adjustable spring acts on the other side. When the outlet pressure drops, the diaphragm moves, opening a valve and allowing air to flow from the inlet to the outlet. Conversely, when the outlet pressure rises, the valve closes. This mechanism automatically maintains a stable outlet pressure.

The desired pressure is set by adjusting a knob, which changes the spring tension. A pressure gauge provides a visual indication of the outlet pressure, allowing for precise monitoring and adjustment.

Modern pressure regulators provide high control accuracy with hysteresis of less than 0,1 bar and the ability to maintain constant pressure even with significant changes in flow. An important parameter is the venting function, which automatically releases excess air when the set pressure is reduced. Without this function, when the set pressure is reduced, the air behind the regulator would remain at the original higher pressure until it was consumed. The maximum flow rate of the regulator must be sufficient to cover the maximum consumption of the pneumatic circuit. An undersized regulator cannot maintain constant pressure during consumption peaks.

The lubricator is the third and optional component of the FRL unit. Its purpose is to add a fine oil mist to the compressed air to lubricate the moving parts of pneumatic components. Piston seals, valve cores, and other moving parts need lubrication to reduce friction and wear. Traditionally, pneumatic components were designed with the assumption that oil mist was present in the compressed air. The lubricator uses the Venturi effect – air flowing through a constriction at high speed creates a vacuum that draws oil from the reservoir. The oil is atomized into microscopic droplets and carried along with the flowing air.

The modern trend in pneumatics is moving towards lubrication-free systems. Current pneumatic components often feature seals made of advanced materials such as polyurethane or PTFE and are designed to operate without external lubrication. This approach offers several advantages: oil-free air does not contaminate products or the environment, which is crucial in industries such as food processing and pharmaceuticals; there is no need to refill lubricating oil or maintain the lubricator; and the components remain cleaner and less prone to sticking.

The main drawbacks are a slightly higher initial cost for components designed for lubrication-free operation and increased sensitivity to contamination and high air humidity. Whether to use a lubricator depends on the type of components installed and the specific requirements of the application.

When a lubricator is used, it is essential to select the correct type of oil. Pneumatic oils must have low viscosity for easy atomization, good adhesion to metal surfaces, resistance to oxidation, and compatibility with sealing materials. Mineral pneumatic oils that comply with ISO VG 32 or equivalent standards are commonly used. Using incorrect oils – such as motor, transmission, or vegetable oils – can damage seals and clog small passages. The amount of oil is controlled by an adjustable dropper, typically set to deliver one drop of oil per 10 to 100 liters of flowing air.

The placement and installation of FRL units follow specific guidelines to ensure proper operation. The unit should be installed as close as possible to the pneumatic

circuit, ideally in a horizontal orientation with the containers facing downwards. The correct order of components is essential: the air filter should be first, followed by the pressure regulator, and finally the lubricator. Air must flow in the direction indicated by the arrows on each component.
The pressure at the regulator inlet should be at least 1 bar higher than the desired outlet pressure to ensure stable control. Exceeding the maximum flow rate of the FRL unit reduces its efficiency and accuracy. Therefore, the unit should be sized according to the maximum flow rate of the pneumatic circuit and the required operating pressure.
FRL units (Fig. 40) are available in a variety of sizes and designs. Compact modular units integrate all three functions – filtration, regulation, and lubrication – into a space-saving package.

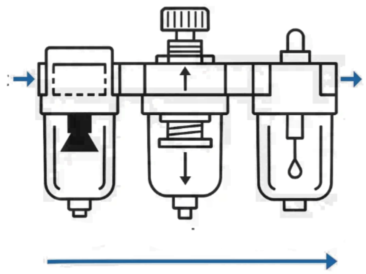

Fig. 40 FRL unit

Separate components allow for more flexible layouts and easier replacement of damaged parts. For demanding applications, specialized FRL units are available with additional features such as coalescing filters for removing oil aerosols, adsorption filters for eliminating odors and vapors, pressure switches for monitoring pressure drops, and flow meters. Leading manufacturers, including Festo, SMC, Parker Hannifin, and IMI Norgren, provide a wide range of FRL units suitable for various applications and flow requirements.

Tab. 6 Air quality requirements according to ISO 8573-1:2010

Purity class (ISO 8573-1)	Solid particles (max. size)	Humidity (max. dew point)	Oil (max. total content)
1	≤ 0,1 μm	≤ -70°C	≤ 0,01 mg/m^3
2	≤ 1 μm	≤ -40°C	≤ 0,1 mg/m^3
3	≤ 5 μm	≤ -20°C	≤ 1 mg/m^3
4	≤ 15 μm	≤ +3°C	≤ 5 mg/m^3
5	≤ 40 μm	≤ +7°C	≤ 25 mg/m^3
6	Neurčené	≤ +10°C	Neurčené

Note: Class 1 = highest purity (laboratories), Class 5 = general industry, a typical FRL unit achieves Class 4 to 5

5.5 Pneumatic cylinders – single and double acting

Pneumatic cylinders are the most common type of pneumatic actuators, converting the energy of compressed air into linear motion. Structurally, they consist of a cylindrical body in which a piston connected to a piston rod moves. The space inside the cylinder body is divided into two chambers, into which compressed air is either supplied or from which it is exhausted. The movement of the piston generates a force at the end of the piston rod, which can be used to perform mechanical work. Pneumatic cylinders are employed in parts handling, sliding mechanisms, gripping, pushing, lifting, and a wide variety of other applications (Fig. 41).

Fig. 41 Various pneumatic cylinders

The basic classification of pneumatic cylinders distinguishes between single-acting and double-acting cylinders, based on how they generate motion. This fundamental difference affects not only the cylinder design but also the way it is controlled, installed, and applied. Choosing between these two types is one of the first critical decisions in designing a pneumatic system.

A single-acting pneumatic cylinder generates active movement in only one direction using compressed air, while the return in the opposite direction occurs passively under the action of an external force. Most commonly, this external force is a built-in spring, but it can also be gravity or an external mechanical load. The design of a single-acting cylinder is relatively simple: it has a single air inlet, an internal space for the spring, and a piston with a piston rod extending from one side of the cylinder.

The operation of a single-acting cylinder (Fig. 42) with a spring return works as follows: when compressed air is supplied to the chamber, the piston moves against the spring force, extending the piston rod.

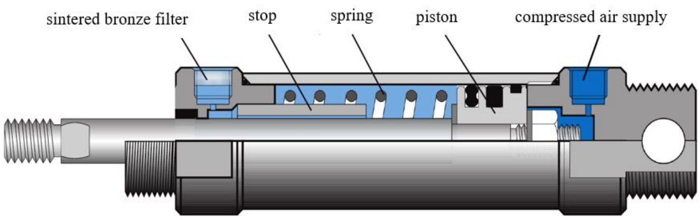

Fig. 42 Single-acting pneumatic cylinder

The force generated by the cylinder is determined by the difference between the force of the air acting on the piston and the counterforce of the spring. When the air supply is interrupted and the exhaust is opened, the spring expands, moving the piston back to its starting position and retracting the piston rod. The retraction speed depends on the spring force, friction, and the load resistance. A typical single-acting cylinder has a stroke of up to 100 mm, as longer strokes would require a disproportionately large and strong spring.

The advantages of single-acting cylinders include simpler design and lower cost, fewer connections (only one air supply and exhaust), automatic return to the starting position even in the event of pressure drop or power failure, which can be a safety feature. Disadvantages include limited stroke, lower force in the extension direction due to spring counteraction, asymmetrical forces in both directions of movement, and the inability to regulate the speed of return movement by throttling the exhaust. Typical applications for single-acting cylinders are pressing and stamping, where the cylinder performs a downward working stroke and gravity or a spring returns it. Gripping parts where a firm hold under pressure and automatic release in the event of pressure failure is required. Clamping workpieces on machines, locking and unlocking mechanisms, controlling valves and flaps. In these applications, one-sided active movement and automatic return are an advantage.

A double-acting pneumatic cylinder (Fig. 43) creates active movement in both directions using compressed air. This type is significantly more versatile and therefore dominates in industrial applications. The design of a double-acting cylinder includes a cylindrical body with a piston attached to a piston rod passing through both end caps. The piston divides the interior of the cylinder into two chambers - front and rear. Each chamber has its own air supply. By supplying compressed air to one chamber while exhausting from the other chamber, the piston moves in the desired direction.

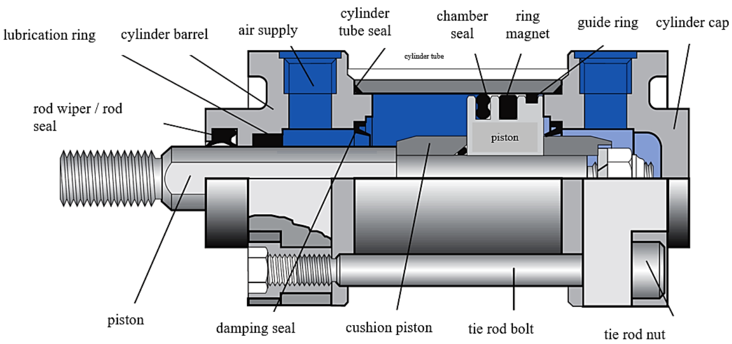

Fig. 43 Double-acting pneumatic cylinder

The principle of operation of a double-acting cylinder allows full control over the movement of the piston in both directions. To extend the piston rod, air is supplied to the rear chamber (on the side opposite the piston rod) and the front chamber is vented to the atmosphere. The air acts on the entire surface of the piston and creates a force that pushes the piston forward. To retract the rod, air is supplied to the front chamber and the rear chamber is vented. The air now pushes the piston in the

opposite direction. An important aspect is the difference in the effective area of the piston in both directions. In the extension direction, pressure acts on the entire surface of the piston, while in the retraction direction, the effective area is reduced by the cross-sectional area of the piston rod.
(principle of operation)
The calculation of pneumatic cylinder forces is based on a simple formula derived from the definition of pressure:

$$F = pA$$

where:
F is the theoretical force in newtons,
p is the working pressure in pascals,
A is the effective piston area in square meters.
For a cylinder with a circular piston, the following applies:

$$A = \pi \frac{d^2}{4}$$

where:
d is the diameter of the piston in meters.
For extension, the diameter of the piston is equal to the inner diameter of the cylinder D. For retraction, the effective area is:

$$A' = \pi \frac{(D^2 - d'^2)}{4}$$

where:
d' is the diameter of the piston rod.
This difference means that the force required for retraction is 5 to 15 percent lower than for extension, depending on the ratio of the diameters.
For practical calculations, the actual force is given, which takes friction losses into account:

$$F_{real} = pA\eta$$

where:
η is the mechanical efficiency of the cylinder, typically in the range of 0,85 to 0,95.
For a cylinder with a piston diameter of 50 mm and a working pressure of 6 bar, the theoretical force during extension is:

$$F = 600000Pa\pi \frac{(0{,}05m)^2}{4} = 600000 \cdot 0{,}001963 = 1178N$$

Considering an efficiency of 0,9, the actual force of the cylinder is approximately 1060 N. For a piston rod with a diameter of 16 mm, the force is around 950 N.
The advantages of double-acting cylinders include controllable movement in both directions, the possibility of speed regulation in both extension and retraction, a wide range of strokes (typically 10 to 1000 mm, with special cylinders reaching several meters), higher structural strength and durability, and the ability to stop the piston at any position by closing both inlets.
Disadvantages include higher cost, the need for two air connections, and more complex control, requiring a valve with at least three ports.

The design of pneumatic cylinders includes several standardized types. Cylinders with end flanges have mounting flanges with threaded holes at the ends, allowing secure attachment to the machine frame. Cylinders with pins feature pins at the ends that fit into support bearings, enabling the cylinder to rotate around the pin axis. This design absorbs lateral forces and is suitable for applications where the piston rod moves along an arc. Rollers with magnetic holders have a groove in the roller body containing permanent magnets that attract the roller to a ferromagnetic surface. Profile cylinders have a special body shape with grooves that allow sensors and clamping elements to be snapped in without screws.

The materials of pneumatic cylinders are selected for strength, corrosion resistance, and low weight. The cylinder body is typically made of aluminum alloy with a hard-anodized surface, or stainless steel for demanding environments. The piston is made of aluminum or plastic, while the piston rod is stainless steel with a hard chrome-plated surface for wear and corrosion resistance. Piston seals are made of synthetic rubber (NBR) for standard applications or polyurethane for higher pressure and longer service life. End dampers are used to absorb kinetic energy when the piston reaches its end positions.

The standardization of pneumatic cylinders ensures interchangeability and widespread availability. The ISO 15552 standard (formerly ISO 6431 and VDMA 24562) defines the dimensions, connections, and properties of pneumatic cylinders, enabling direct replacement between products from different manufacturers. This standard applies to cylinder diameters of 32, 40, 50, 63, 80, 100, 125, 160, 200, 250, and 320 mm. Compliant manufacturers provide compatible products with guaranteed performance characteristics.

With proper maintenance and operating conditions, pneumatic cylinders can achieve a service life of tens of millions of cycles. The primary wear components are the seals, whose longevity depends on air quality, movement speed, load, and temperature. Contaminants such as dirt and moisture significantly reduce lifespan. Regular maintenance includes inspection and replacement of seals, checking screw tightness, lubrication of moving parts, and monitoring end dampers.

5.6 Cylinder speed control

Controlling the speed of a pneumatic cylinder is an important task in the design of pneumatic systems. An uncontrolled cylinder moves at the maximum speed determined by the available air supply, which often leads to impacts at end positions, mechanical shocks, noise, and reduced component lifespan. Speed regulation allows smooth, controlled movements suitable for delicate handling, synchronization of multiple cylinders, and overall higher quality of automated processes.

The basic principle of controlling a pneumatic cylinder's speed is regulating the air flow. The piston speed is directly proportional to the volumetric flow of air entering or leaving the cylinder. Reducing the air flow slows down the cylinder movement, while increasing the flow accelerates it. Flow control is achieved using throttle valves, which have an adjustable orifice that limits the amount of air passing per unit of time.

A unidirectional throttle valve (throttle check valve, flow control valve) is a standard component for controlling the speed of pneumatic cylinders. It consists of an adjustable throttle and a parallel-connected check valve. In one flow direction, air passes through the throttled section, where the flow is limited by the adjustable screw. In the opposite direction, the check valve opens, allowing air to pass with minimal resistance. This arrangement allows speed regulation of the cylinder in only one direction, while in the opposite direction, the cylinder moves at maximum speed (Fig. 44).

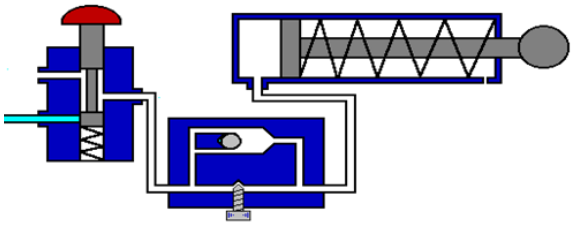

Fig. 44 Schematic diagram of a one-way throttle valve

The location of the throttle valve in a pneumatic circuit has a significant impact on the quality of speed control. There are two basic methods of throttling: supply-side throttling and exhaust-side throttling (Fig. 45).

Fig. 45 Throttle valve

In supply-side throttling, a unidirectional throttle valve is installed in the air supply to the cylinder. The air entering the cylinder is restricted, which slows the piston movement. This method is less stable because full working pressure is not established in the cylinder chamber, making the cylinder sensitive to load changes. When the load increases, the cylinder may slow down or stop; when the load decreases, it accelerates. Exhaust-side throttling is the preferred method. Here, the one-way throttle valve is placed in the exhaust line of the cylinder. The air supplied to the cylinder's working chamber is unrestricted, ensuring full working pressure. The exhaust air from the opposite chamber is throttled, generating resistance that slows the piston movement. This configuration is much more stable, as the cylinder always operates at full pressure and is less sensitive to variations in load. For this reason, most industrial applications use exhaust-side throttling as the standard method for speed control.
For a double-acting cylinder, where speed regulation is required in both directions of movement, two unidirectional throttle valves are used. One valve controls the

extension speed by throttling the exhaust from the rear chamber, while the other valve controls the retraction speed by throttling the exhaust from the front chamber. Each valve is independently adjustable, allowing for different speeds in the extension and retraction directions. Typical applications include scenarios where a fast working stroke and a slow return stroke are desired, or where precise synchronization of equal speeds in both directions is required.
(principle of operation)
The throttle valve is adjusted by turning the adjustment screw, which changes the size of the cross-section through which air can flow. Typically, the so-called meter-out principle is used, where the air leaving the cylinder is throttled. The optimal setting is determined experimentally during system commissioning. Fully closing the throttle would block the cylinder’s movement, while opening it too much would result in excessive speed. The objective is to achieve a setting that provides the desired speed with smooth, jerk-free motion.
The ability to control the speed of pneumatic cylinders is limited by the compressibility of air. At very slow speeds, below approximately 10 mm/s, a stick-slip effect can occur, where the piston moves in jerky increments rather than smoothly due to transitions between static and dynamic friction of the seals. This effect prevents very slow and precise movements using simple throttling. For applications requiring fine speed control or precise positioning, servo-pneumatic systems with proportional valves, position sensors, and closed-loop feedback are used.
The effect of load on cylinder speed is another factor that complicates precise control. Although exhaust throttling provides better stability than intake throttling, the cylinder still remains sensitive to load variations. A cylinder moving a light load travels faster than one with a heavy load at the same throttle setting. When the load varies significantly during movement, the cylinder speed also changes. This behavior is due to the compressibility of air – under higher loads, the air in the working chamber is compressed more, resulting in slower piston movement.
Modern solutions for precise speed control employ proportional pneumatic valves, which allow electronic regulation of airflow. These valves contain an electromagnetic actuator controlled by current, which continuously adjusts the valve core position and thus the air flow cross-section. A control signal from a PLC or microcontroller sets the desired speed. When combined with position sensors, a closed-loop control system can be implemented to automatically compensate for load variations and achieve precise speed and position control. Although this technology is more expensive than simple throttling, it delivers significantly better performance for demanding applications.
Synchronizing the movement of multiple cylinders is a common requirement in automation. When using simple throttle valves, it is not possible to achieve perfect synchronization because each cylinder has slightly different friction, load, and internal characteristics. For applications requiring precise synchronization, mechanical cylinder connections (common piston rod, rigid guides) or electronic synchronization using position sensors and servo-pneumatic systems are used. Simpler applications

that tolerate slight differences in position can use parallel-connected cylinders with identical throttling.
Shock absorbers are an important addition to pneumatic cylinders operating at higher speeds. Standard pneumatic cylinders have a built-in end damper that closes the exhaust port before reaching the end position and creates an air cushion to absorb the shock. An adjustable screw valve allows the damping intensity to be regulated. For heavy loads or high speeds, external hydraulic shock absorbers are used to absorb kinetic energy. Without adequate damping, mechanical shocks occur, shortening the service life of the cylinder, mounting elements, and the entire device.

5.7 Multi-way pneumatic valves – basic types

Pneumatic valves are control elements that determine the direction of flow, pressure, and flow rate of compressed air in a pneumatic system. While pneumatic cylinders perform mechanical work, valves determine when, where, and how fast the air should flow. Without valves, a pneumatic system would be nothing more than a static pressure vessel. Valves give it dynamics, intelligence, and the ability to perform complex sequences of movements.
(principle of operation)
The basic designation of pneumatic valves uses a pair of numbers X/Y, where X indicates the number of ports (connections) of the valve and Y indicates the number of switching positions that the valve can occupy. A port is a physical connection of a pipe to a valve – air supply from a source, connections to actuators, exhausts to the atmosphere. A switching position is a discrete state in which certain ports are connected and others are closed. By switching between positions, the valve controls the flow of air (Fig. 46).

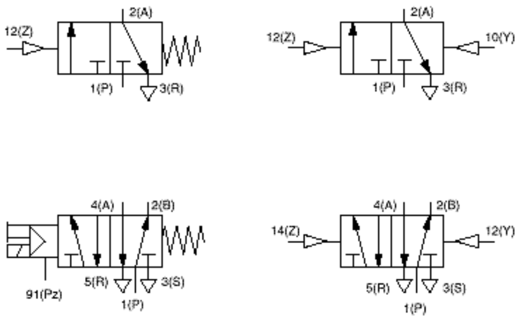

Fig. 46 Schematic symbols for multi-way valves

A 2/2 valve has two ports and two positions. The two ports are the air inlet P (pressure) and the working outlet A. The two positions are open (ports P and A connected) and closed (ports P and A separated). The 2/2 valve acts as a simple air switch – either air flows or it does not. It is used for switching the air supply on and off, controlling single-acting cylinders, controlling pneumatic tools, and wherever a simple on/off function is required. The 2/2 valve can be normally closed (NC) or normally open (NO) in its basic position. The basic position is the position the valve occupies without a control signal.

(principle of operation)
The 3/2 valve has three ports and two positions. The three ports are the supply port P, the working outlet A, and the return/exhaust port R. In one position, port P is connected to port A (air flows to the actuator) and port R is closed. In the other position, port P is closed and port A is connected to port R (air from the actuator is discharged into the atmosphere). The 3/2 valve is primarily designed for controlling single-acting cylinders. In the basic position, it can be normally closed (3/2 NC) or normally open (3/2 NO). The application depends on whether the cylinder should be retracted or extended in the basic state.
(principle of operation)
The 5/2 valve has five ports and two positions. The five ports include the supply port P, two working ports A and B connected to both chambers of the double-acting cylinder, and two exhaust ports R and S. In one position, port P is connected to port A and port B to exhaust port R – air flows into one chamber of the cylinder and the other chamber is emptied. In the second position, port P is connected to port B and port A to exhaust S – the direction of air flow is reversed and the cylinder moves in the opposite direction. The 5/2 valve is a standard control valve for double-acting pneumatic cylinders. It allows full control of cylinder movement in both directions.
The 5/3 valve (Fig. 47) has five ports and three positions.

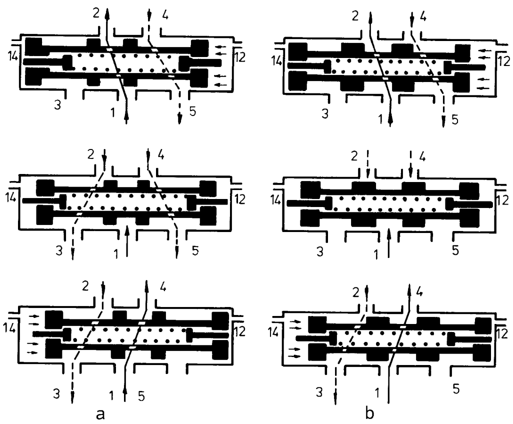

Fig. 47 5/3 valve

The ports are the same as for the 5/2 valve, but there is a middle third position between the two extreme positions. The function of the middle position depends on the type of valve and can perform various states. The closed middle position blocks all ports – the cylinder stops in the position reached and remains blocked by air pressure in both chambers. The exhaust middle position connects both working chambers to the exhausts – the pressure in the cylinder drops and the cylinder can be moved by an external force. The pressure middle position connects the supply to both working chambers – the cylinder is pressurized on both sides. The 5/3 valve is used for advanced applications requiring a stop function, floating position, or special modes.
(principle of operation)

In terms of design, pneumatic valves are divided into seat valves and slide valves. A seat valve uses a rubber or plastic diaphragm or cone seal that presses against the seat. Switching is performed by the movement of the diaphragm or cone, which opens or closes the flow paths. The advantages of seat valves are excellent sealing even at low pressure, a clean design without wear and tear on parts, and low air consumption during pilot control. Disadvantages include the higher force required for switching and the limited service life of elastic parts.

A slide valve contains a cylindrical slide with sealing rings that moves in the cylindrical body of the valve. The slide has bores and grooves connecting the individual ports depending on the position. The advantages of slide valves are low force required for switching, high switching speed, and long service life. Disadvantages include higher sensitivity to contamination and the need for high-quality lubrication. Modern slide valves use polyurethane or PTFE seals with long service life and low friction.

The method of returning the valve to its basic position divides valves into monostable and bistable. A monostable valve (single-sided) has one stable position to which it returns under the action of a spring after the control signal is removed. A continuous control signal is required to switch the valve. The advantage is a defined safe state in the event of a control failure. A bistable valve (double-sided) has two stable positions and, after switching, remains in the new position even after the control signal is removed. A control signal pulse is required to change the position. The advantage is zero energy consumption to maintain the position. Bistable valves are used for functions requiring a memory function.

The graphic symbols of pneumatic valves are standardized by ISO 1219-1:2012 for unambiguous communication. The valve symbol consists of rectangles representing the individual positions. Inside the rectangles are lines and arrows showing the flow paths between the ports. A closed port is terminated by a line (⊥), an open port by an arrow (→). The ports are marked with the letters P, A, B, R, S according to their function. Valve switching is indicated by arrows outside the valve symbol.

The size of pneumatic valves is selected according to the required maximum air flow. The flow through the valve depends on the nominal connection diameter, the internal cross-section of the flow paths, and the valve design. Manufacturers specify the flow capacity in normal liters per minute (l/min under normal conditions) or as a Kv value indicating the flow rate in special units. An undersized valve limits the speed of the cylinder and reduces the available force. An oversized valve unnecessarily increases costs and dimensions.

5.8 Valve control

The method by which a valve switches between its positions determines the degree of automation in a pneumatic system and its ability to integrate into modern control architectures (Fig. 48). Pneumatic valves can be actuated in various ways, ranging from direct manual operation by an operator to advanced electronic control via programmable logic controllers (PLCs).

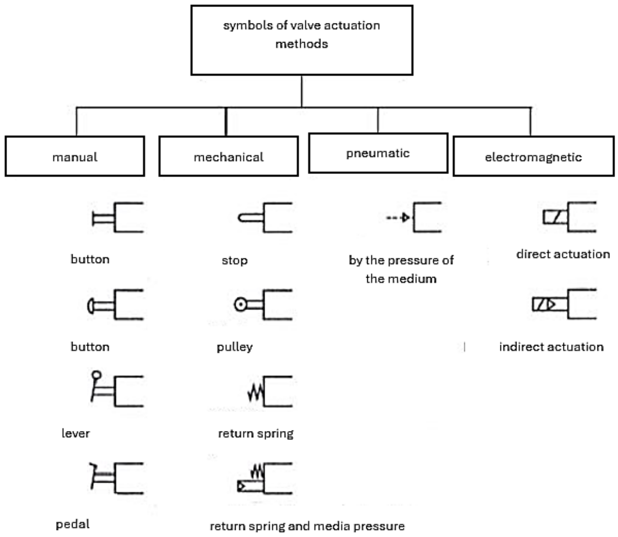

Fig. 48 Different ways of controlling valves

Manual control is the simplest actuation method, where the operator directly applies mechanical force to the valve's control element. A hand lever or push-button is mechanically linked to the valve mechanism, and its movement initiates the switching action. Foot pedals allow the valve to be operated by foot, leaving the operator's hands free for other tasks. Rotary switches are used when multiple valve positions must be distinguished.

Manual control is commonly applied in simple devices, for manual machine operation, emergency actuation, and system testing. Its advantages include independence from external power sources, simplicity, and high operational safety. However, it also has notable limitations: it requires the operator's physical presence, has a slower response time, and cannot support automation.

Mechanical control uses physical contact between the cylinder or moving mechanism and the valve switching element. The roller limit switch has a rotating roller that tilts when it comes into contact with a moving part and triggers the valve. The plunger is a fixed protrusion on the cylinder that presses on the switching element when it moves. A spring lever has a spring that causes the valve to switch when mechanical force is applied and returns to its original position when the force is removed. Mechanical control allows you to create automatic sequences where one cylinder triggers another cylinder when it reaches its end position. The advantages are simplicity, reliability, and low cost. Disadvantages include wear on mechanical parts, sensitivity to vibration and dust, and the need for direct mechanical contact.

Pneumatic control uses compressed air itself to switch the valve. The pilot valve has a separate pilot port to which control air pressure is supplied. This pressure acts on a diaphragm or piston inside the valve, causing it to switch. Pneumatically operated valves can be monostable (spring returns to home position) or bistable (pilot pressure on both sides, valve remembers position). The advantages of pneumatic control include high reliability in aggressive environments, fast switching, the ability to operate without a power supply, and natural compatibility with pneumatic systems.

The disadvantages are air consumption for control, the need for additional pilot distribution, and more complex logic circuits.
Electric control using electromagnetic coils (solenoids) is the most modern and widespread method of controlling pneumatic valves in industry. A solenoid valve contains an electromagnetic coil which, when an electric current is applied, creates a magnetic field that attracts a movable ferromagnetic core. The movement of the core causes the valve to switch either directly or via a pneumatic pilot valve. A monostable solenoid valve has one coil and a spring - when voltage is applied, the valve switches; when the voltage is removed, the spring returns to its original position. A bistable solenoid valve has two coils - one for switching to one position, the other for switching to the other position. The valve remembers its position even after the power is disconnected.
The electrical supply voltage of solenoid valves is usually 24 V DC (direct current), which is the standard voltage in industrial automation. Some valves operate at 230 V AC (alternating current), but these are used less frequently due to higher safety risks. The power consumption of the coil ranges from a few watts for small valves to 20 watts for large valves. Solenoid valves have fast switching times in the order of milliseconds, which allows for high-frequency cycles. The service life of electric coils is tens of millions of switching operations when operated correctly.
Solenoid valves are connected to the control system using cables or directly via industrial buses. Traditionally, each coil is connected to the PLC (programmable logic controller) outputs with a separate cable. Modern solutions use valve terminals – compact blocks containing dozens of valves with a central air supply and electronic connection via an industrial bus (Profibus, EtherCAT, IO-Link). Valve terminals save time during installation, reduce the number of cables, and enable diagnostics of the status of individual valves (Fig. 49).

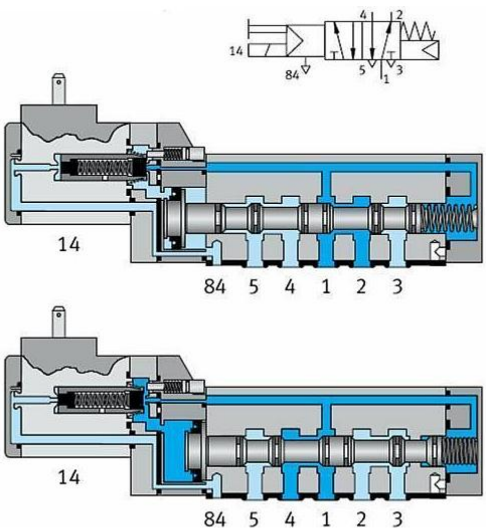

Fig. 49 5/3 electromagnetically controlled valve

Cylinder position reporting is an important function for system reliability. Magnetic sensors located on the valve detect the position of the moving core and provide an electrical signal confirming valve switching. This signal is evaluated in the control system to check for proper operation. If a fault is detected (the valve has not switched), the system can perform a safety response. The sensors are typically proximity switches or Hall sensors integrated into the valve body.

Proportional pneumatic valves are an advanced category that allows for continuous control of air flow or pressure. Unlike standard combustion valves with discrete positions, a proportional valve allows the valve core to be set to any position between fully closed and fully open. Control is achieved by an analog electrical signal (e.g., 0-10 V or 4-20 mA) or digital PWM modulation. A proportional flow valve allows precise control of the speed of cylinder movement. A proportional pressure valve allows dynamic changes in working pressure. Proportional valves are key to the implementation of servo-pneumatic systems with precise position and force control.

Logic pneumatic elements perform simple logical functions without the need for an electrical power supply. An AND valve provides an output signal only when both input signals are present.

Tab. 7 Comparison of different types of valve control

Control method	Principle of operation	Advantages	Disadvantages	Typical applications
Manual	Direct control by human force (button, lever, wheel).	Simplicity, reliability, no external power required.	Requires operator presence, slow response times, unsuitable for automation.	Hand-held machines, testing equipment, emergency control.
Mechanical	Control by physical contact with a moving part of the machine (e.g., limit switch).	Sequence automation without electronics, reliability in a mechanical system.	Wear and tear on contact surfaces, requires direct contact.	Simple sequential circuits, cylinder end position detection.
Pneumatic (Pilot)	Control by compressed air supplied to the control port.	Operation without electricity (safe in potentially explosive environments), fast switching.	Higher air consumption, more complex circuit designs compared to PLCs.	Purely pneumatic logic circuits, chemical industry.
Electric solenoid	Control by electric current through a coil (solenoid) that generates a magnetic field.	Easy integration with PLCs and control systems, precise timing, remote control.	Requires electricity, possible electromagnetic compatibility (EMC) issues.	Industrial automation (standard use), production lines.
Proportional	Smooth change in flow or pressure proportional to the electrical signal.	Precise speed/position control, servo functions, fine adjustment.	High cost, complex control and calibration, requires special control cards.	Demanding applications requiring precise positioning, gas mixing, pressure control.

It is used in safety circuits that require two conditions to be met simultaneously, such as two-hand machine start-up. An OR valve provides an output signal when at least one of the input signals is present and is used for alternative control from multiple locations. A shuttle valve switches between two inputs, and the output is connected to the input with the higher pressure. Logic elements make it possible to create simple control circuits without electronics, which is advantageous in extreme environments. The safety aspects of valve control require special attention. A valve malfunction can lead to unexpected cylinder movement and serious injury. Safety valves must comply with EN ISO 13849 for safety-related functions. Dual-channel control with monitoring ensures that a malfunction in one channel does not create a hazardous situation. The emergency stop must be able to immediately stop all movements by disconnecting the power supply to the valves. Brake (holding) valves secure the cylinder in position even in the event of a pressure loss. Safety interlocks prevent dangerous movements from starting until all required safety conditions are met.

6 ELECTROPNEUMATICS

Electropneumatics is a specialized branch of pneumatics in which compressed air remains the working medium, but the control functions are performed by electrical components. This hybrid approach combines the advantages of pneumatic systems – such as simplicity, safety, and low maintenance costs – with the precision, flexibility, and automation capabilities of electrical control.

The basic principle of electropneumatics is founded on the interaction between pneumatic and electrical components through dedicated converters. An electro-pneumatic converter transforms an electrical signal into pneumatic pressure, while a pneumatic-electrical converter performs the opposite function. This combination makes it possible to benefit from the power and robustness of compressed-air actuators while implementing sophisticated control algorithms using electrical circuits or programmable logic controllers (PLCs).

The historical development of electropneumatics is closely tied to the increasing automation demands of industrial production. While purely pneumatic systems were suitable for simple applications, growing requirements for accuracy, repeatability, and integration into complex production lines led to the emergence of electropneumatic solutions. The first industrial applications appeared in the automotive sector, where fast and reliable control of handling equipment was required while maintaining a high level of operational safety.

Today, electropneumatics is used across a wide range of industries. In the food industry, it is applied in packaging technology, where the speed of pneumatic actuators is combined with the precise timing of electrical control. In the automotive industry, electropneumatics provides reliable operation of clamping devices on machine tools and assembly lines. The pharmaceutical industry requires clean and safe solutions, which electropneumatics can offer thanks to the absence of flammable liquids and the possibility of using non-toxic working media.

Current trends in electropneumatics are moving toward even closer integration with digital technologies. The Industry 4.0 concept requires communication capabilities of individual components, operational data collection, and the ability to perform remote monitoring. Modern electropneumatic systems therefore increasingly incorporate integrated sensors, communication modules, and support for industrial networks such as PROFINET or EtherCAT. This convergence of pneumatic, electrical, and information technologies opens up new possibilities for predictive maintenance, energy-efficiency optimization, and flexible reconfiguration of production processes.

6.1 Solenoid valves and coils

The solenoid valve is a key component of electro-pneumatic systems, converting electrical signals into pneumatic action. Its function is to control the flow of compressed air using electromagnetic force acting on a movable valve. Understanding the operating principle, design, and properties of solenoid valves is essential for the effective design and proper operation of electro-pneumatic systems.

6.1.1 Principle of operation of an solenoid valve

The core of a solenoid valve is an electromagnetic coil, which generates a magnetic field when an electrical voltage is applied. This field acts on a ferromagnetic armature (core), causing it to move and change the position of the valve body. In the rest state, when no voltage is applied to the coil, the armature's position is determined by a mechanical spring. When the coil is energized, the magnetic force overcomes the spring force and moves the armature to its operating position. When the voltage is removed, the spring returns the armature to its original position.

There are two basic types of solenoid valves, depending on their default (idle) state. A normally closed (NC) valve is closed when no voltage is applied and allows air to flow only when the coil is energized. Conversely, a normally open (NO) valve is open in its idle state and closes when voltage is applied. The choice of the appropriate type depends on the safety requirements of the application and its energy consumption.

The design of a solenoid valve consists of several basic components. The valve body is usually made of aluminum alloy or zinc and contains channels for air supply and exhaust. Inside the body is a valve seat, which ensures a tight seal in one of the positions. The armature, made of ferromagnetic material, moves to control the airflow. The coil is wound from copper wire and generates a magnetic field when an electric current passes through it. A spring ensures that the armature returns to its rest position, and its stiffness determines the required force of the electromagnet. Sealing elements, most often made of rubber or polyurethane, ensure the system's airtightness.

6.1.2 Directly controlled and pilot-controlled valves

Solenoid valves can be divided into directly controlled and pilot-controlled valves according to their control method. Directly controlled valves use electromagnetic force directly to move the valve body, which controls the main air flow. This design is suitable for smaller flow rates and lower pressures, as the electromagnet must overcome not only the force of the spring, but also the pressure forces acting on the valve body (Fig. 50).

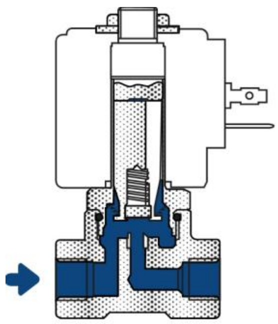

Fig. 50 Directly controlled solenoid valve

Pilot-operated valves use electromagnetic force only to control a small pilot valve, which then controls the main valve using the pressure force of compressed air. The main valve body is larger and its movement is ensured by the pressure difference between its sides. This design allows for switching larger flow rates and operating at higher pressures, as the electromagnet only controls a small pilot valve with low force requirements (Fig. 51).

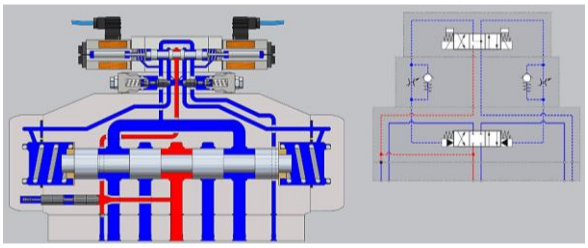

Fig. 51 Indirectly electromagnetically controlled valve

However, pilot-operated valves have one important operating condition. For them to function properly, there must be a minimum pressure difference between the inlet and outlet pressures, usually in the range of 0,3 to 1 bar. This pressure difference provides sufficient force to move the main valve body. If the pressure difference is insufficient, the valve may malfunction or the switching time may be prolonged.

6.1.3 Classification of solenoid valves

Solenoid valves are classified according to the number of ports and the number of positions. This classification is indicated by the symbol X/Y, where X represents the number of ports and Y represents the number of switching positions. A two-way valve (2/2) has two ports – an inlet and an outlet – and two positions: closed and open. This type is used for simple on/off flow control. A three-way valve (3/2) has three ports and two positions. The ports include the compressed air inlet, the outlet to the actuator, and the exhaust (vent). In one position, the inlet is connected to the outlet, and in the other position, the outlet is connected to the exhaust. This type of valve is suitable for controlling single-acting pneumatic cylinders. A five-way valve (5/2) has five ports and two positions. The ports consist of the compressed air supply, two outlets to the actuator, and two exhausts. This type of valve is used to control double-acting pneumatic cylinders, allowing alternating filling and venting of both cylinder chambers (Fig. 52).

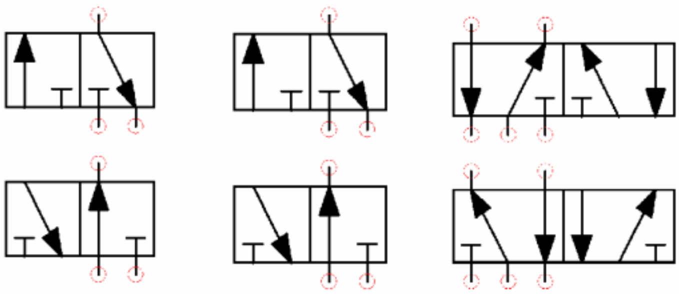

Fig. 52 Schematic representation of various valves 2/2, 3/2, 5/2

6.1.4 Technical parameters of solenoid valves

Selecting a suitable solenoid valve requires knowledge of its technical parameters. The nominal pressure indicates the maximum operating pressure at which the valve can function continuously without damage. Typical values range from 0 to 10 bar for standard pneumatic applications. The nominal flow rate characterizes the maximum volume of air that can pass through the valve at a given pressure drop. This parameter is usually specified in liters per minute under standard conditions (20°C, 1,013 bar). The valve response time is the interval between the application of the control signal and the valve body reaching its final position. Solenoid valves typically have a response time of 10 to 50 milliseconds, enabling fast switching cycles. Electrical parameters include the rated coil voltage, which is standardized in industrial applications as 24 V DC, 110 V AC, or 230 V AC. Coil power typically ranges from 2 to 10 W, depending on the valve size.
(principle of operation)
The service life of a solenoid valve depends on the quality of its construction, operating conditions, and switching frequency. High-quality valves can achieve a service life of 10 to 30 million switching cycles. Another important parameter is the leakage rate, which indicates the amount of air passing through a closed valve. High-quality seals ensure minimal leakage, which is crucial for the system's energy efficiency and control accuracy.
The operating environment has a significant impact on valve selection. Ambient temperature affects the properties of sealing materials and can also influence the magnetic characteristics of the coil. Standard valves typically operate in the range of -10°C to +60°C, while special designs allow operation beyond this range. The degree of protection according to IEC 60529 indicates the valve's resistance to the ingress of solid particles and water. For industrial environments, a minimum protection rating of IP54 is recommended, and for more demanding conditions, IP65 or higher is preferred.

6.2 Electrical control of pneumatic systems

Electrical control of pneumatic systems represents a fundamental conceptual shift from purely pneumatic control. While compressed air remains the working medium, providing mechanical energy, the control functions are performed by electrical components. This hybrid approach combines the power advantages of pneumatics with the flexibility, precision, and automation capabilities offered by electrical control.

6.2.1 Basic principles of electrical control

Electrical control of pneumatic systems uses electrical signals to operate solenoid valves, which in turn regulate the flow of compressed air to pneumatic actuators. The electrical signal can be binary, where the valve is either on or off, or analog, allowing continuous regulation of flow or pressure through proportional valves.The basic control loop of an electro-pneumatic system consists of several components. Sensors detect the current state of the system, such as the position of a cylinder piston, the

system pressure, or the presence of a workpiece. This information is converted into electrical signals and transmitted to the control unit. The control unit, which can range from a simple relay circuit to a programmable logic controller (PLC), evaluates the input signals and generates output control signals based on programmed logic. These signals operate solenoid valves, which then control pneumatic actuators to perform the required mechanical work.
Signals between the electrical and pneumatic subsystems are converted by special transducers. An electro-pneumatic transducer converts an electrical signal – typically in the range of 4-20 mA or 0-10 V – into a proportional pneumatic pressure. This function is essential for the precise control of forces and positions of pneumatic actuators. A pneumatic-electric transducer performs the opposite function, converting pneumatic pressure into an electrical signal suitable for processing by the control unit. Additionally, any solenoid valve with a binary output can be considered a simple electro-pneumatic converter (Fig. 53).

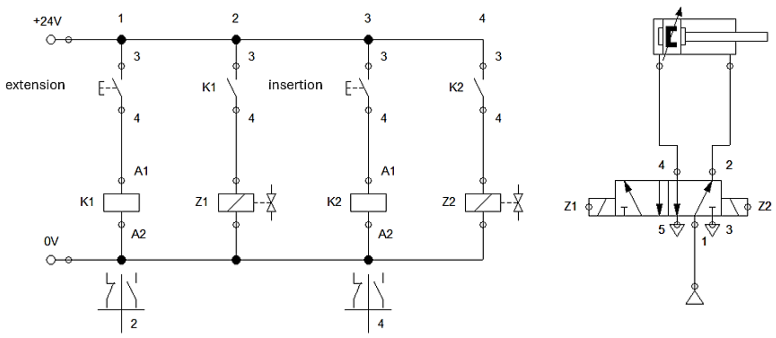

Fig. 53 Example of an electro-pneumatic control diagram

6.2.2 Advantages of electro-pneumatics

Electropneumatic systems offer several advantages over purely pneumatic solutions. The primary benefit is the simpler control of complex sequences. While purely pneumatic circuits require intricate valve arrangements to implement sequential processes, electropneumatics allow the same logic to be realized using simpler electrical circuits or PLC software. This capability significantly reduces the costs of design, implementation, and especially subsequent modifications to the control logic.
Another key advantage is the possibility of automation. The integration of programmable logic controllers enables the execution of complex control algorithms, timing sequences, conditional decision-making, and communication with higher-level systems. Modern PLCs provide functions such as regulation, production data monitoring, fault diagnostics, and remote monitoring. These capabilities are either unavailable in purely pneumatic systems or technically very difficult to implement.
Reduced failure rates are achieved due to fewer moving mechanical parts in the control section of the system. Electrical contacts and semiconductor switches have a considerably longer service life than pneumatic valves at the same switching frequency. Fault diagnosis is also easier in electropneumatic systems, thanks to the ability to sense electrical signals and evaluate them in real time.

Electropneumatic systems require less space than purely pneumatic solutions. Electrical cables occupy less space than pneumatic hoses and are more flexible to install. A control panel with a PLC and relays takes up less space than an equivalent panel with pneumatic valves. This advantage is particularly significant when modernizing existing equipment, where space is often a limiting factor.
The control accuracy and repeatability of electropneumatic systems are higher due to more precise position sensing, accurate timing, and the possibility of implementing feedback control. Digital sensors provide clear information about the system's status without the need to set threshold values, as is necessary with pneumatic sensors. Programmable timers in the PLC enable precise control of time sequences with millisecond resolution.

6.2.3 Limitations of electro-pneumatics

Despite its numerous advantages, electro-pneumatics also has certain limitations that must be considered when selecting the appropriate type of control. The most significant limitation is that it cannot be used in explosive environments. Electrical sparks generated when contacts switch can act as a potential source of ignition in the presence of flammable gases or dust. Purely pneumatic systems are inherently safe in this regard because they do not use electrical components that could produce sparks. For the use of electro-pneumatics in explosive environments, it is necessary to employ special components with an explosion-proof design in accordance with the STN EN 60079 standard. These components utilize one of the certified protection methods, such as internal pressure, encapsulation, increased safety, or intrinsic safety. However, such solutions are significantly more expensive than standard components and require specialized installation and maintenance.
Another limitation is the higher initial investment compared to simple pneumatic systems. While purely pneumatic control may be cheaper for basic applications, for more complex systems the difference is offset, and electro-pneumatics can become more economical. The decision on the type of control should be based on an overall economic analysis that considers not only initial costs but also operational, maintenance, and potential future modification costs.
Electropneumatic systems require a power supply, which can be a disadvantage in some cases. In the event of a power failure, all control functions are lost, whereas a purely pneumatic system can remain partially functional thanks to compressed air reservoirs. For critical applications, it is therefore necessary to provide backup power sources or design the system to enter a safe state in the event of a power failure.

6.3 Relay logic

Relay logic is a traditional and still widely used method for implementing control functions in electro-pneumatic systems. Although programmable logic controllers (PLCs) are gradually replacing relays in new applications, understanding relay logic remains important for maintaining existing equipment and for grasping the fundamentals of industrial control. Additionally, relay circuits offer high reliability and operational transparency, which is advantageous in simpler applications.

6.3.1 10.4.1 Principle of relay operation

A relay is an electromagnetically operated switch that allows a higher-power circuit to be controlled using a low-power control signal. The basic design of a relay consists of an electromagnetic coil, an armature attached to a spring, and a set of contacts. When voltage is applied to the coil, a magnetic field is generated that pulls the armature against the force of the spring. This movement of the armature changes the state of the contacts – normally open contacts close, and normally closed contacts open.

(principle of operation)

Each relay contains several types of contacts. The common contact, labeled COM, is the center contact that switches between the other two contacts. The normally closed contact, NC, is connected to the common contact when de-energized and disconnects when the relay is energized. The normally open contact (NO) is disconnected from the common contact in the de-energized state and connected when the relay is energized. A single physical relay element can contain multiple independent sets of contacts, allowing simultaneous control of multiple circuits.

6.3.2 Ladder diagrams

A ladder diagram is a graphical representation of relay circuits. The name comes from its resemblance to a ladder, where the two vertical lines represent power rails and the horizontal lines between them resemble ladder rungs. This notation is intuitive and allows for quick understanding of the control circuit's function.

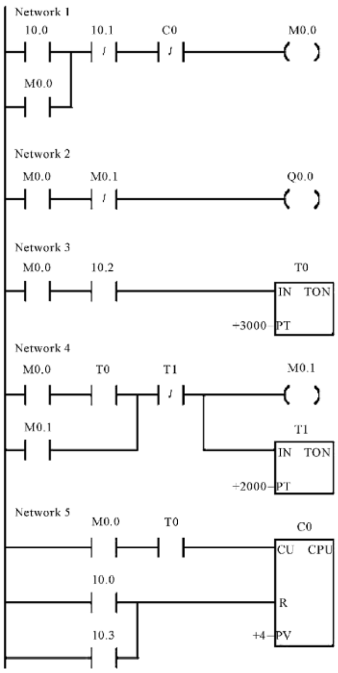

Fig. 54 Example of a ladder diagram

The basic structure of a ladder diagram consists of two vertical lines labeled L1 and L2, which represent the positive and negative poles of the power supply. Between these lines are horizontal branches containing input elements on the left and output elements on the right. Input elements, such as buttons, limit switches, or relay contacts, are always drawn on the left between L1 and the output element. Output elements, such as relay coils or solenoid valves, are connected directly to line L2.
The rules for drawing ladder diagrams ensure uniformity and clarity. STOP functions, which are intended to interrupt operation, are connected in series within the control branch. START functions, intended to initiate an operation, are connected in parallel. All devices are drawn in their normal state, i.e., in the state they occupy when power is disconnected and the mechanism is at rest. This rule is important for correctly understanding the circuit's function (Fig. 54).

6.3.3 Basic logical functions

Relay circuits enable the implementation of all basic logic functions necessary for controlling pneumatic systems. The AND function requires that all input conditions be met simultaneously. In a ladder diagram, this is achieved by connecting the input contacts in series. Current can only flow to the output element when all series contacts are closed. A practical example is starting the movement of a cylinder only when the cylinder is in its home position and the start button is pressed at the same time.
The OR function requires at least one of the input conditions to be met. It is implemented by connecting the input contacts in parallel. Current can flow to the output element through any of the parallel contacts. A typical example is an emergency stop system that can be activated from multiple locations using parallel-connected emergency buttons.
The latching function is important for maintaining the output state even after the start button is released. It is implemented by a parallel contact of the output relay itself, connected in parallel to the start button. When the start button is pressed, the relay coil is activated, which closes its own contact and maintains its activation even after the button is released. The circuit is stopped only by pressing the stop button, which is connected in series and interrupts the power supply to the coil.

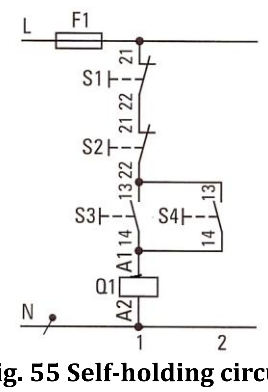

Fig. 55 Self-holding circuit

Time functions are implemented using time relays (Fig. 56), which provide a delay in switching on or off.

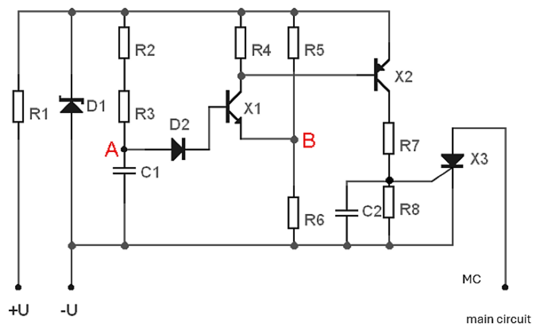

Fig. 56 Time relay

An on-delay time relay begins counting the set time after the activation of the input signal and switches its contacts once this time has elapsed. This type is used for delayed starts or for controlling the time limit of an operation. An off-delay time relay switches its contacts immediately upon activation but returns them to their original state only after the set time has elapsed following the deactivation of the input signal.

6.3.4 Sequential control using relays

Sequential control using relays allows the implementation of a sequence of steps, where each step must be completed before the next one begins. A typical application is the control of a pneumatic cylinder that must perform a specific sequence of movements. The basic sequence A+ A- means that the cylinder first extends and then returns to its starting position.

Sensors detecting the end positions of the cylinder are required to implement this sequence. Limit switch a0 signals the retracted state of the cylinder, while limit switch a1 signals the extended state. The control circuit must ensure that when the start button is pressed, solenoid Y1 is activated, causing the cylinder to extend. Once the extended position is reached and sensor a1 is activated, solenoid Y1 is deactivated, and the cylinder returns to its starting position under the influence of a spring or counterpressure.

More complex sequences require the coordination of multiple cylinders. The sequence A+ B+ B- A- means that cylinder A extends first, then cylinder B extends, then cylinder B retracts, and finally cylinder A retracts. This type of sequence requires the use of multiple relays to remember the status of each step and ensure the correct order of operations (Fig. 57).

A problem in the design of sequential circuits can arise when the same cylinder must move in both directions within a single cycle. This situation requires a special connection using memory relays to prevent ambiguity in the state. A modern solution to this problem is provided by programmable logic controllers, which allow for easier implementation of complex sequences.

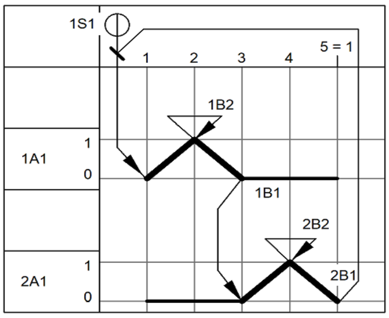

Fig. 57 Sequential diagram

6.4 Programmable logic controllers

Programmable logic controllers, or PLCs, represent a modern and flexible method for controlling electro-pneumatic systems. A PLC is an industrial computer specifically designed for control applications that executes programmed logic and controls output devices based on the status of input signals. The introduction of PLCs into industrial practice revolutionized automation, as it allowed simple programming and modification of control algorithms without the need to change the hardware configuration.

6.4.1 Basic PLC structure

The basis of every PLC is a microprocessor, which serves as the computing unit of the system. The microprocessor executes the program stored in memory and controls individual inputs and outputs based on this program. The PLC memory is divided into several areas. Program memory contains the control program and configuration parameters, while data memory stores the current values of inputs, outputs, internal variables, and timers. Modern PLCs use non-volatile memory, which retains its contents even when the power is disconnected (Fig. 58).

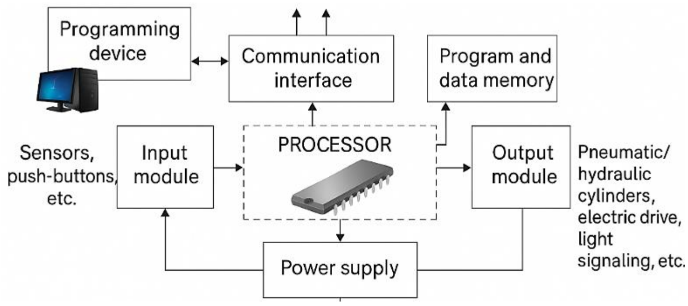

Fig. 58 Block diagram of PLC

The input/output system ensures communication between the PLC and the external world. Input modules receive signals from sensors, buttons, and other sensing devices. These signals can be digital, representing two states (on/off), or analog, representing a continuous range of values. Output modules provide signals to control actuators such as solenoid valves, contactors, or frequency converters. Like inputs, outputs can be digital or analog.

The power supply provides electrical power to all PLC components. Industrial PLCs typically operate at 24 V DC to power the input/output modules, while the internal electronics may operate at a lower voltage. Communication interfaces allow the PLC to communicate with other devices, such as host computers, operator panels, or other PLCs. Modern systems support industrial communication protocols such as PROFINET, EtherCAT, Modbus, or DeviceNet.

6.4.2 Historical development of PLCs

The history of programmable logic controllers began in 1968-1969, when General Motors announced a competition to replace complex relay panels on its production lines. The main requirement was the ability to easily change the control logic without physically altering the wiring. The winner of the competition was Bedford Associates, with a prototype called MODICON 084, which stands for Modular Digital Controller.

The first generations of PLCs had very limited capabilities. They were only used to replace basic relay functions, such as switching outputs based on a combination of input signals. Programming was performed using special programming panels with mechanical switches. New functions, such as timers, counters, and arithmetic operations, were gradually added. The second generation of PLCs introduced programming using personal computers and expanded communication possibilities with other devices.

The third generation of PLCs, which began to appear in the 1990s, brought a significant increase in computing power and memory. It enabled the implementation of complex algorithms, control, and communication via industrial networks. The current, fourth generation of PLCs is characterized by high performance, support for Internet connectivity, integrated web servers, and the ability to process data directly in the PLC. These features enable the implementation of Industry 4.0 concepts, such as predictive maintenance and remote production monitoring.

6.4.3 IEC 61131-3 standard

The IEC 61131-3 standard, first published in 1993, is an international standard for programming industrial control systems. The third part of this standard defines five standardized programming languages, which enable program portability between different PLC manufacturers and facilitate programmer training. Before the introduction of this standard, each PLC manufacturer had its own proprietary programming language, which made the work of integrators and maintenance technicians more difficult.

The first defined language is Ladder Diagram, a graphical language based directly on relay logic. Its advantage is its intuitiveness for technicians accustomed to electrical diagrams and the simplicity of implementing Boolean logic. Function Block Diagram is the second graphical language, displaying the program as interconnected functional blocks. This language is suitable for complex control algorithms and flow-oriented programs.

Structured Text is a textual language similar to the Pascal or C programming languages. It is suitable for implementing complex algorithms, mathematical calculations, and data structures. Instruction List is a low-level language consisting of a list of instructions similar to assembler code. This language was popular in the past due to its fast execution, but in the current fourth edition of the standard from 2025, it has been marked as deprecated and its use is not recommended. Sequential Function Chart is the fifth language, designed for sequential and parallel control, which graphically displays system states and transitions between them.

6.4.4 Ladder Diagram in PLC

Ladder Diagram in a PLC environment (Fig. 59) retains the basic philosophy of relay logic but works with virtual contacts and coils instead of physical components. Each PLC input is represented by a contact that can be normally open or normally closed. Each PLC output is represented by a coil. In addition, the PLC provides internal variables, often called tags or marker bits, which act as virtual relays and are used to store intermediate results and states.

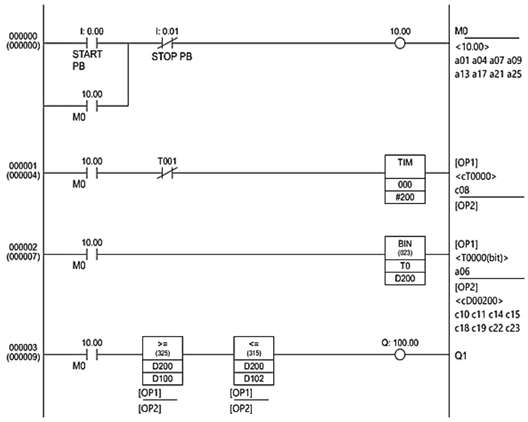

Fig. 59 Example of a PLC program in a ladder diagram

The basic elements of a ladder diagram include contacts and coils. A normally open contact is represented in a PLC by two vertical lines, similar to parallel lines. This contact closes when the corresponding variable is in the TRUE or 1 state. A normally closed contact is represented by the same lines with a diagonal line through them. This contact closes when the corresponding variable is in the FALSE or 0 state. An output coil is represented by a circle or a pair of brackets and activates the corresponding output or sets an internal variable.

PLCs also provide more advanced instructions. Timers allow the implementation of time delays for switching outputs on or off. The TON instruction represents an on-delay timer that starts counting once the input is activated and switches the output on after the set time has elapsed. The TOF instruction represents an off-delay timer that switches on immediately and switches off only after a period of time has elapsed since the input was deactivated. Counters allow events, such as the number of pieces or

cycles, to be counted. The CTU instruction counts up with each rising edge of the input, while CTD counts down.
For electro-pneumatic applications, it is important to map inputs and outputs correctly. Inputs are designated by the letter I, followed by the byte and bit number; for example, I0.5 means bit 5 in byte 0 of the input data. Outputs are designated by the letter Q; for example, Q0.1 means bit 1 in byte 0 of the output data. Internal variables are designated by the letter M; for example, M1.0. This structured addressing allows each element of the program to be uniquely identified.

6.4.5 Advantages of PLCs over relay logic

Programmable logic controllers (PLCs) offer several advantages over traditional relay-based logic. The primary benefit is the flexibility to modify control logic. Changing the function of a system requires only an update to the program on the computer, which can be done within minutes. In contrast, relay logic would require physically rewiring connections, a process that is time-consuming and prone to errors. This flexibility is especially valuable when production requirements change frequently or when new processes are being tested.
Diagnostics and troubleshooting are significantly easier in PLC systems. Programming software enables online monitoring of the current status of all inputs, outputs, and internal variables. Technicians can observe program execution in real time and identify exactly which part of the logic is malfunctioning. Many PLCs also provide alarm logs and event history tracking, which greatly simplify the analysis of intermittent issues.
Complex functions that would require dozens of components in relay logic can be implemented in a PLC using only a few instructions. Mathematical operations such as addition, subtraction, multiplication, and division are standard features in PLCs. Control algorithms, including PID control, are available as ready-made function blocks. Communication with other systems via industrial networks further enables seamless integration into complex production environments.
PLC program documentation is a standard component of the development environment. Programs can be printed, including comments and symbolic names, which makes it easier for other technicians to understand their functionality. The ability to save multiple program versions and compare the differences between them supports effective change management and enables quick restoration of previously working configurations.
PLC systems also offer high reliability due to the absence of moving mechanical parts in the logic section of the system. While relays have a limited contact lifespan, the electronic components used in PLCs do not experience mechanical wear. Modern PLCs achieve a mean time between failures measured in tens of years, making them suitable for critical applications that demand high availability.

6.5 Sensors in electropneumatics

Sensors are critical components of electro-pneumatic systems because they provide feedback on the current state of the process to the control unit. Without reliable information about the position of actuators, pressure in the system, or the presence of workpieces, the control system cannot perform its function effectively. Selecting the right sensors requires an understanding of their operating principles, technical parameters, and application requirements.

6.5.1 Magnetic contactless switches

Magnetic contactless switches, also known as proximity switches or reed sensors, are among the most widely used position sensors in electro-pneumatic systems. These sensors detect the magnetic field of a permanent magnet embedded in the piston of a pneumatic cylinder. They operate on the principle of a reed relay closing under the influence of a magnetic field, which generates an electrical signal indicating the piston's position (Fig. 60).

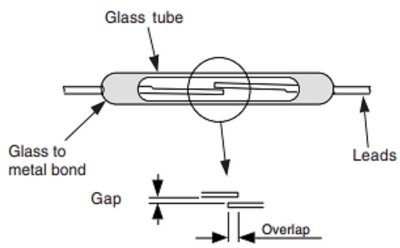

Fig. 60 Magnetic reed sensor

The design of reed sensors is simple and highly reliable. Each sensor consists of a glass ampoule containing two ferromagnetic contacts in an inert atmosphere. In their normal state, the contacts are separated by a small air gap. When a magnet approaches, the contacts are drawn together by magnetic force, closing the electrical circuit. Once the magnet is removed, the elasticity of the contacts ensures that they reopen. The glass ampoule protects the contacts from dust and oxidation.

The main advantage of magnetic contactless switches is the absence of mechanical wear, since there is no physical contact between the sensor and the moving part of the cylinder. Their service life can reach hundreds of millions of switching cycles. Another benefit is that the sensor can be mounted externally on the cylinder without altering its internal structure. Sensors are typically secured in special grooves on the cylinder using screws or sliding holders.

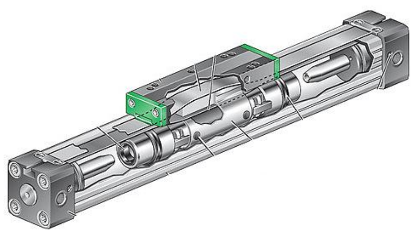

Fig. 61 Pneumatic actuator with integrated magnets

Key technical parameters of reed sensors include the switching distance, which defines the maximum distance between the sensor and the magnet at which switching occurs. Typical switching distances range from 5 to 15 mm, depending on the magnet’s strength and the sensor design. The repeatability of the switching position is usually between 0.1 and 0.5 mm, which is sufficient for most pneumatic applications. Electrical parameters specify the maximum switching current and voltage, typically 0.5 to 1 A at 24 V DC.

6.5.2 Limit mechanical switches

Mechanical limit switches (Fig. 62) detect position through direct physical contact with a moving part of the mechanism. Although magnetic contactless switches are gradually replacing mechanical switches in modern applications, mechanical switches continue to play an important role due to their simplicity, reliability, and low cost. They are especially suitable for environments with strong magnetic interference, where non-contact sensors may fail to operate.

Fig. 62 Limit mechanical switches

The basic component of a mechanical limit switch is the actuator, which can have various designs. A lever with a roller allows detection from different angles and reduces wear due to the rolling motion of the roller. A straight push pin is suitable for detecting motion in a precisely defined direction. A flexible tongue bends under pressure and returns to its original position when released. The choice of an appropriate actuator depends on the direction and speed of the approaching object.

The electrical section of the switch contains one or more contact blocks. Each block may include normally open contacts, normally closed contacts, or a combination of both. The switching capacity is determined by the contact material and size. Typical values for industrial applications are 5 to 10 A at 250 V AC. For low-voltage circuits controlled by PLCs, contacts with a capacity of 0.5 to 1 A at 24 V DC are sufficient.
(principle of operation)

The installation of mechanical limit switches requires careful adjustment of the position and control element. The switch must be positioned so that it switches reliably when the desired position is reached, but at the same time, mechanical damage due to excessive travel must be prevented. Manufacturers usually specify the maximum approach speed and maximum mechanical transient stroke that the switch can withstand without damage.

6.5.3 Pressure sensors and switches

Pressure sensors and switches provide information about the pressure within a pneumatic system. Pressure switches generate a binary signal when a set threshold is reached, while pressure sensors provide an analog signal proportional to the current pressure. Both types are essential for system diagnostics, pressure level control, and safety functions.

The operation of pressure sensors is based on the deformation of a flexible element under pressure. A diaphragm sensor uses a thin metal or ceramic diaphragm that deflects proportionally to the applied pressure. This deformation can be detected using various methods. Strain gauge sensors employ metal or semiconductor strain gauges attached to the diaphragm, whose electrical resistance changes with deformation. Capacitive sensors measure changes in capacitance between the deformed diaphragm and a fixed opposite electrode. Piezoelectric sensors generate an electrical voltage proportional to the mechanical stress within the crystal.

In addition to the sensing element, pressure switches also contain a switching unit with an adjustable threshold pressure. When this pressure is reached, the switch contacts either close or open. The threshold is typically set mechanically using a spring preloaded by a screw or electronically in programmable switches. The switch hysteresis defines the difference between the pressures at which it switches on and off, ensuring stable operation without contact chattering near the threshold value.
(principle of operation)

Selecting an appropriate pressure sensor requires consideration of the measuring range, accuracy, output signal type, and operating environment. For pneumatic systems with pressures up to 10 bar, sensors with a range of 0-10 bar or 0-16 bar are suitable. The accuracy of pressure sensors typically ranges from 0.5% to 2% of the full scale. The output signal may be voltage (0-10 V), current (4-20 mA), or digital via an industrial communication bus. For demanding industrial environments, a protection rating of IP65 or higher is recommended.

6.6 Basic principles of sequential control

A sequential process can be described as a series of steps and transitions. Each step represents a stable state of the system, during which it performs a specific action or waits for a condition to be met. Transitions between steps occur once a defined condition is satisfied, which may involve reaching a particular position, the expiration of a time interval, the activation of a sensor, or a combination of multiple conditions.
(principle of operation)

The graphical representation of sequential processes uses a functional diagram (Fig. 63), also known as a function sequence graph. In this diagram, steps are shown as rectangles and transitions as horizontal lines.

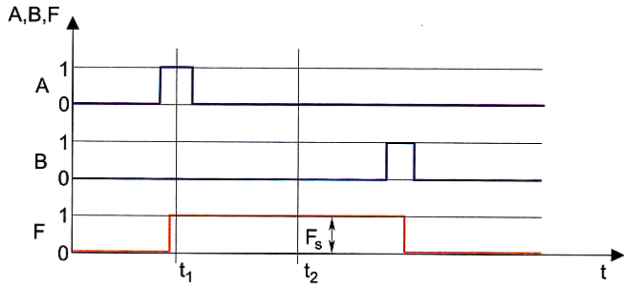

Fig. 63 Sequence diagram

The conditions for each transition are written alongside the corresponding lines, while the actions performed in each step are listed within the rectangles representing the steps. This type of diagram provides a clear overview of the entire process and simplifies the design of control logic.

In PLCs, sequential control is implemented using state variables that represent individual steps. Each step corresponds to a single binary variable, which is TRUE when the step is active and FALSE when it is inactive. Only one step can be active at a time, ensuring deterministic system behavior. Transition to the next step occurs by resetting the current step and setting the next step once the transition condition is satisfied.

6.6.1 Implementing a sequence in Ladder Diagram

Programming sequential control in a Ladder Diagram requires a systematic approach. The basic program structure includes one branch for each step in the sequence. Each branch contains the contact corresponding to the current step, the conditions for transitioning to the next step, and the outputs that should be active during this step. The first part of the branch ensures that the current step is deactivated and the next step is activated, while the second part controls the output devices during the step.

For a simple sequence involving a single cylinder (A+ and A-), two steps are required. Step 1 represents the extension of the cylinder, and Step 2 represents its retraction. The program starts at Step 1. The transition from Step 1 to Step 2 occurs when the cylinder reaches its extended position, signaled by sensor a1. The transition from Step 2 back to Step 1 occurs when the cylinder reaches its retracted position, signaled by sensor a0, and the start button is pressed to initiate a new cycle.

Implementation begins by defining internal variables for the steps. Let us assign M10.0 to Step 1 and M10.1 to Step 2. The first branch of the program contains the contacts M10.0 AND a1, meaning that if Step 1 is active and the cylinder has reached the extended position, the transition to Step 2 will occur. This branch deactivates M10.0 and activates M10.1. The second branch contains the contacts M10.1 AND a0 AND START, indicating a transition back to Step 1 once the cylinder is retracted and the start button is pressed. Output control is handled in separate branches. Solenoid Y1, which extends the cylinder, is activated when Step 1 is active. The program includes a branch with contact M10.0 and coil Q0.0 representing Y1. During Step 2, solenoid Y1 is de-energized, and the cylinder retracts due to the spring or back pressure in the case of a double-acting cylinder with a double solenoid.

6.6.2 More complex sequences

Sequences involving multiple cylinders require careful coordination of their movements. A typical sequence is A+ B+ B- A-, in which cylinder A is first extended, followed by cylinder B, then cylinder B is retracted, and finally cylinder A is retracted. This sequence involves four steps, with each step corresponding to a single movement of one cylinder. A critical aspect in designing such sequences is ensuring that the transition conditions are mutually exclusive. There must be no situation in which the conditions for multiple transitions are met simultaneously, as this would create ambiguity regarding which step should be activated. This property is achieved through careful design of the transition conditions, which rely on position sensors for both cylinders. Time-controlled sequences require the use of timers. For instance, if cylinder A must remain extended for 5 seconds before retracting, a timer must be added to the transition condition. The timer is activated upon entering the step with cylinder A extended, and its expiration forms part of the condition for transitioning to the next step.

6.6.3 Sequential Function Chart v PLC

The Sequential Function Chart (SFC) is a graphical programming language defined by the IEC 61131-3 standard, specifically designed for sequential and parallel control. This language provides a more intuitive approach to programming sequential processes compared to Ladder Diagram, as its structure directly corresponds to the functional diagram of the process (Fig. 64).

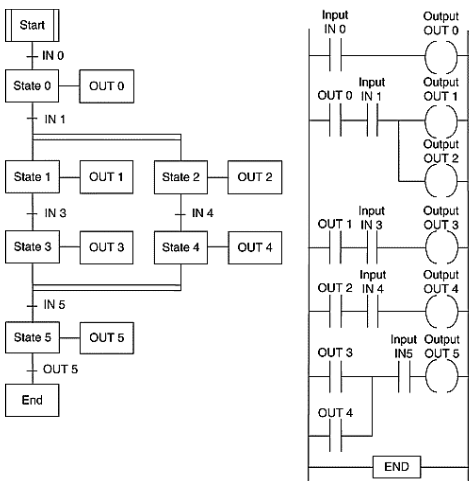

Fig. 64 Example of an SFC program

The basic elements of SFC include steps, transitions, and actions. Steps are represented as rectangles and correspond to stable states of the system. The first step in the program is marked with a double line. Transitions are shown as horizontal lines perpendicular to the program flow and contain Boolean conditions that must be

satisfied to move to the next step. Actions are displayed to the right of the steps and define the operations performed during each step.
Programming the sequence A+ B+ B- A- in SFC begins with defining four steps corresponding to the individual movements of the cylinders. Each step is assigned an action that activates or deactivates the corresponding solenoid: Step 1 activates Y1, Step 2 activates Y2, Step 3 deactivates Y2, and Step 4 deactivates Y1. Transitions between steps are based on the status of limit switches.
The advantage of SFC lies in its clarity when representing complex sequences and its ability to easily illustrate parallel processes. The main drawback is that support for this language may be limited on some PLC platforms, and technicians are generally less familiar with it compared to Ladder Diagram. Nevertheless, for educational purposes, SFC is an excellent tool for understanding the principles of sequential control.

6.7 BSafety of electro-pneumatic systems

Safety is a critical aspect in the design and operation of electro-pneumatic systems. Pneumatic actuators can generate significant forces and high movement speeds, which may cause serious injury to operators. Electrical components also pose a risk of electric shock. The combination of pneumatic and electrical hazards necessitates a systematic approach to safety, based on international standards and established safety principles.

6.7.1 ISO 13849-1 standard

ISO 13849-1 defines safety requirements and provides guidelines for the design of safety-related parts of machine control systems. This standard applies to all types of machines, regardless of the technology used, including electrical, hydraulic, pneumatic, and mechanical systems. For electro-pneumatic systems, ISO 13849-1 provides a framework for designing safety functions and evaluating their effectiveness.
The basic concept of the standard is the Performance Level (PL), which quantifies the ability of safety-related parts of a control system to perform a safety function under defined conditions. Performance Levels are expressed on a five-point scale from PLa to PLe, where PLa represents the lowest and PLe the highest level of safety. Each Performance Level corresponds to a range of probabilities for dangerous failures per hour of operation.
The required Performance Level for a specific safety function is determined based on a risk assessment. The standard provides a graphical tool based on three parameters. The severity of potential injury is assessed on a two-point scale: S1 represents minor injuries, and S2 represents serious injuries or death. The frequency and duration of exposure to the hazard are assessed as F1 for rare to occasional and F2 for frequent to continuous. The possibility of avoiding the hazard is assessed as P1 for possible under certain conditions and P2 for almost impossible. The combination of these parameters determines the required Performance Level, PLr.

6.7.2 Categories of safety systems

ISO 13849-1 defines five categories of electropneumatic system architectures based on their ability to withstand faults. Category B represents the basic level, in which proven components and design principles are used, but no special fault-tolerance measures are implemented. This category is suitable only for low-risk applications.

Category 1 requires the use of proven components and design principles with higher quality and reliability standards than Category B. This category is suitable for applications where the probability of failure is low and the consequences of a failure are not critical.

Category 2 involves periodic testing of safety functions. The system must be designed to allow regular verification of the functionality of safety circuits. Testing can be scheduled or integrated into the machine's operating cycle.

Category 3 employs a redundant design in which critical functions are duplicated. The system contains two independent channels performing the same safety function. A monitoring system detects differences between the channels and, if a difference is detected, initiates a transition to a safe state. Some faults may not be detected, but a single-channel fault must not result in a loss of the safety function.

Category 4 represents the highest level of safety, featuring a redundant design and the capability to detect all relevant faults. The system must remain functional even after a fault occurs, and any fault must be detected at the latest when the safety function is next requested. This category is intended for critical applications where failure of the safety function could result in serious injury or death.

6.7.3 Safety functions in electro-pneumatics

Safety features in electro-pneumatic systems include several mechanisms designed to reduce the risk of injury. The primary safety function is the emergency stop, which allows dangerous movements to be halted immediately using easily accessible emergency buttons. According to IEC 60947-5-5, emergency buttons must be red and located in easily reachable positions.

Implementing emergency stop in electro-pneumatic systems requires ensuring that all pneumatic drives are brought to a safe state when the emergency button is pressed. This may involve stopping movement, reducing system pressure, or mechanically locking moving parts. To achieve a higher Performance Level, redundant elements should be used, such as dual emergency buttons connected to two independent safety channels.

Protective devices that restrict access to hazardous areas during machine operation are another important safety feature. Safety doors equipped with interlocking switches prevent dangerous movements from starting when the doors are open. Light barriers detect the presence of a body or limb in a hazardous area and either prevent the cycle from starting or immediately stop any movement in progress.

Safe pressure relief ensures that compressed air is safely vented from hazardous actuators in the event of an emergency stop or when a safety door is opened. This function is performed by safety valves that are directly controlled by the safety circuit

and do not depend on the correct functioning of the PLC program. Special valves with forced venting are used to ensure reliable pressure relief even in the event of a malfunction.
Two-hand control ensures that the operator keeps both hands on the control buttons during dangerous movements, preventing hands from entering the hazard zone. This function requires both buttons to be pressed simultaneously, with a time tolerance of no more than 0.5 seconds. Both buttons must remain pressed throughout the entire hazardous movement, and releasing either button must immediately stop the movement.

6.8 Applications of electro-pneumatics in industry

Electropneumatic systems are widely used in modern industry due to their combination of power, speed, precision, and flexibility. The selection of an electro-pneumatic system for a specific application is based on an analysis of process requirements, economic factors, and operating conditions. Understanding typical applications aids in the design of new systems and in troubleshooting existing equipment.

6.8.1 Automotive industry

The automotive industry is one of the most important application areas for electro-pneumatic systems. Car production lines require fast, precise, and repeatable operations when assembling thousands of components. Electro-pneumatic systems are used to secure car bodies during welding, handle drive units during assembly, and accurately position components before joining.
Welding robots operate in conjunction with electro-pneumatic clamping devices. The car body arrives at the welding station, where pneumatic clamping cylinders precisely position and secure it. A PLC controls the clamping sequence, verifies correct positioning using sensors, and authorizes the robots to start welding. After welding operations are complete, the PLC controls the release of the car body and its transfer to the next station. The entire cycle typically takes 60 to 90 seconds and must be repeatable with an accuracy better than 0,5 mm.
Car painting requires precise handling of car bodies in an aggressive environment filled with solvents and paint aerosols. Pneumatic systems are preferred over hydraulics in this environment due to the absence of risk of paint contamination by oil in the event of a leak. Electropneumatic control ensures the synchronized movement of multiple rollers transporting the car body through the paint booth. The system must operate in a potentially explosive atmosphere, which requires the use of certified components with an explosion-proof design.
Assembly lines use electro-pneumatic systems for pick-and-place operations. Pneumatic grippers pick up a component from a magazine, rollers transport it into the assembly position, and release it after assembly. The PLC coordinates the movements of multiple manipulators working in parallel and ensures that there is no collision between moving parts. Vision systems verify the presence and orientation of

components before assembly, and the PLC uses this information to decide whether to continue or discard defective pieces.

6.8.2 Food and pharmaceutical industry

The food and pharmaceutical industries require the highest standards of hygiene and cleanliness. Electropneumatic systems in these industries use special components made of stainless steel or plastics approved for food contact. All surfaces must be easy to clean and resistant to aggressive cleaning agents. Pneumatic systems are preferred over hydraulics because air leaks do not contaminate the product.

Packaging technology is driven by electro-pneumatic systems for high speed and accuracy. Rollers transport the film, lift and close the packages, activate the sealing jaws, and mark the finished packages. Modern packaging machines achieve speeds of 60 to 120 packages per minute, which requires precise synchronization of all movements. The PLC controls the timing of operations with millisecond precision and monitors hundreds of sensors that detect the position of the film, the presence of the product, and the quality of the seal.

Electropneumatically controlled filling technology ensures precise dosing of products into bottles or cans. Pneumatic cylinders move the containers under the filling nozzles, lift them into contact with the nozzles, and, after filling, transport them to the sealing station. The dosing of the liquid is controlled by a proportional pneumatic valve operated by an analog PLC output, allowing precise volume adjustment with a tolerance better than 1%.

The pharmaceutical industry requires complete traceability and validation of all processes. Electropneumatic systems in this sector record every operation, including timestamps, pressure values, cylinder positions, and operator identification. The PLC communicates with higher-level systems such as MES or ERP, which maintain a complete record of the production batch. In the event of a complaint, it is possible to trace back the exact conditions under which the product was manufactured.

6.8.3 Machining and mechanical engineering

Machine tools use electro-pneumatic clamping systems for rapid workpiece changeover. Pneumatic clamps secure workpieces with a precisely defined force controlled by a pressure regulator. Excessive clamping force can deform the workpiece, while insufficient force may allow the workpiece to move during machining. Sensors verify correct clamping before machining begins, and the PLC prevents the cycle from starting if clamping is incorrect.

Automatic tool change on CNC machines uses pneumatic cylinders to move the tool magazine and clamp the tool into the spindle. The entire tool change cycle typically takes 3 to 8 seconds, which significantly affects machine productivity in small-batch production with frequent tool changes. The PLC coordinates the movements of the spindle, tool magazine, and pneumatic grippers to prevent collisions and damage to the tool or machine.

Feeding devices for bar stock use pneumatic cylinders to feed the material and clamp it during cutting. Electropneumatic control ensures precise dosing of the cut length with a tolerance of 0.1 mm. The system operates in conjunction with encoder feedback or a laser length gauge, which allows compensation for mechanical tolerances and achieves high repeatability.

Feeding devices for bar stock use pneumatic cylinders to feed the material and clamp it during cutting. Electro-pneumatic control ensures precise length control of each cut piece with a tolerance of 0.1 mm. The system operates in conjunction with encoder feedback or a laser length gauge, which allows compensation for mechanical tolerances and achieves high repeatability.

Chips are removed from the workpieces after machining using air nozzles connected to an electro-pneumatic system. The PLC controls the blowing sequence, activating the nozzles in the correct order and with precise timing. The system can also include air ionization to eliminate static electricity, which causes small particles to adhere to the workpiece surface.

6.8.4 Logistics and warehouse systems

Automated warehouses use electro-pneumatics to handle pallets, cartons, and individual products. Pneumatic cylinders drive conveyor belts, lift and lower transfer mechanisms, and open and close gates on rack stackers. Modern automated warehouses achieve a throughput of thousands of items per hour, which requires coordination of hundreds of pneumatic actuators.

Sorting systems use pneumatic switches to direct packages according to their destination. Barcodes or RFID tags identify the package, and the PLC determines the destination branch of the conveyor, activating the pneumatic cylinder at the correct moment to move the package to the appropriate belt. The system must operate with high reliability, as incorrect sorting can lead to costly complaint processes.

Palletizing robots work with electro-pneumatic grippers to pick up cartons and place them on pallets. The gripper must generate sufficient force for a secure grip without damaging the contents of the carton. A pressure regulator controls the clamping force depending on the type of product. Sensors in the gripper detect successful gripping, and the PLC prevents the robot from moving if gripping is unsuccessful.

Identification stations use pneumatic cylinders to orient products before scanning barcodes or RFID tags. The cylinder rotates the product to the correct position, the camera scans the code, and the PLC processes the information. If the reading is unsuccessful, the system automatically repeats the attempt or rejects the product for manual inspection.

7 HYDRAULICS SYSTEMS AND THEIR SYSTEMATIC COMPARISON WITH PNEUMATICS

Hydraulic systems are among the most efficient methods for transmitting high forces and power in modern mechatronics, achieving overall efficiencies of 40–60% compared to only 10–30% for pneumatics. This chapter provides a comprehensive academic overview of the physical principles, components, properties of hydraulic fluids, and a systematic comparison with pneumatic systems across seven key parameters.

It is essential for mechatronics students to understand that hydraulic fluids are approximately 10,000 times less compressible than air. This fundamental property determines system characteristics such as high rigidity, precise positioning, and the ability to transmit enormous forces in compact dimensions. Nevertheless, pneumatics retains its dominant position in applications requiring cleanliness, speed, and simplicity. The choice between hydraulic and pneumatic systems is not a matter of better or worse technology, but of selecting the right tool for a specific application.

7.1 Physical Fundamentals and Components of Hydraulic Systems

Hydraulics is based on three fundamental physical principles that define the behavior of fluids under pressure. Pascal's law states that the pressure in a closed container filled with liquid is the same in all directions. This principle allows for force transmission, expressed by the relationship:

$$\frac{F_2}{F_1} = \frac{S_2}{S_1}$$

where:

the ratio of forces corresponds to the ratio of piston areas.

This principle forms the basis of hydraulic presses and jacks, where a small input force applied to a small piston generates a much larger output force on a larger piston.

The continuity equation is another fundamental principle, expressing the conservation of mass in a fluid system. It states that the volumetric flow rate remains constant along a closed circuit:

$$Q = Sv = constant$$

where:

$Q$is the volumetric flow rate, $v$is the fluid velocity,

S is the cross-sectional area of the flow channel.

This principle explains why fluid velocity increases in narrower channels and is essential for designing hydraulic circuits, pumps, and actuators.

Bernoulli's equation

$$p + \frac{(\rho v^2)}{2} = constant$$

expresses the conservation of energy in a flowing fluid, whereby an increase in velocity leads to a decrease in static pressure.

The incompressibility of liquids is a key property that distinguishes hydraulics from pneumatics. Hydraulic oil has a bulk modulus of approximately 15,000 bar, while air

has only 1.4 bar at atmospheric pressure, representing a difference of 10,000:1. In practice, this means that at a pressure of 200 bar and a volume of 1000 cm^3, the volume of hydraulic oil will only decrease by approximately 13.3 cm^3 (1.3%), while air would compress dramatically. This property ensures almost instantaneous power transmission and high system rigidity. However, it should be noted that the presence of only 1% air in hydraulic oil reduces the bulk modulus by approximately 50%, which significantly affects the stability and natural frequency of the system. Therefore, thorough venting of hydraulic systems is critically important.
Hydraulic pumps are divided into three main categories. External gear pumps are the simplest and cheapest, achieving pressures of up to 250 bar (exceptionally 315 bar), flow rates of 1-250 l/min, and efficiency of 85-92%. They are used in simple and moderately demanding applications (Fig. 65).

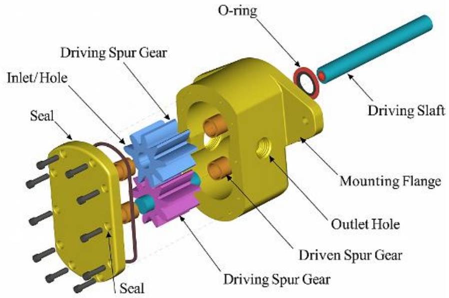

Fig. 65 External Gear Pump

Vane pumps use retractable vanes pressed against an eccentric stator. They typically operate at pressures up to 210 bar (commonly 160-175 bar), achieve flow rates of 5-250 l/min, and have efficiencies of 85-90%. Vane pumps are characterized by quieter operation and lower pulsations compared to gear pumps, making them suitable for applications requiring smooth and stable flow.
Axial piston pumps represent the pinnacle of hydraulic pump technology. They can achieve pressures of 350-450 bar, and up to 700 bar in special applications, with flow rates ranging from 10 to over 1000 l/min and efficiencies of 92-97%. Axial piston pumps allow for precise power and flow regulation and are widely used in the most demanding industrial and mobile hydraulic applications (Fig. 66).

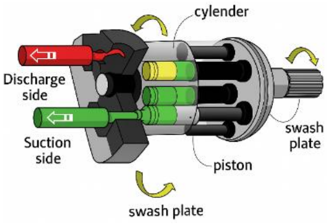

Fig. 66 Axial piston pump

(principle of operation)
Hydraulic cylinders are designed in three basic versions. Single-acting cylinders have pressure applied to only one side of the piston, with the return movement provided

by a spring or external force. They are mainly used in lifting devices and presses. Double-acting cylinders with a single-sided piston rod are the most common in practice, with the extension force $F_1 = p \cdot S_1$ being greater than the retraction force $F_2 = p(S_1 -$ piston rod area). The area ratio $S_1/S_2$is typically 1,3 to 2:1, resulting in different forces and speeds in each direction of movement. Telescopic cylinders consist of a set of nested pistons of different diameters, allowing a large stroke within a compact overall dimension.

Control valves form the nervous system of hydraulic circuits. Pressure valves regulate the maximum pressure (safety valves), reduce the pressure in part of the circuit (reducing valves), or ensure sequential switching (sequence valves). Directional control valves (designated, for example, 4/3 for 4 ports and 3 positions) control the direction of fluid flow and thus the direction of cylinder movement. Flow control valves regulate the speed of actuators: simple throttle valves limit flow, while pressure-compensated valves maintain a constant flow regardless of the load. Proportional and servo valves allow continuous electrical control of pressure, flow, and direction with high precision and dynamic response.

Hydraulic fluids must meet several critical requirements. Viscosity is the most important property, with ISO VG 46 (kinematic viscosity 46 mm^2/s at 40°C) being the most common grade for industrial applications. The viscosity index (VI) indicates the sensitivity of viscosity to temperature; higher values (typically 95–110 for mineral oils, up to 150+ for synthetic oils) correspond to smaller changes in viscosity with temperature. The flash point of mineral oils is typically 200-250°C, while the pour point ranges from –15 to –30°C. Synthetic hydraulic fluids (HFD-U) offer better performance at extreme temperatures and higher fire safety, with a flash point of 250-260°C. Biodegradable fluids according to ISO 15380 include HETG (vegetable oils, > 70% biodegradability within 28 days), HEES (synthetic esters, > 60% biodegradability, offering the best technical properties), and HEPG (polyglycol-based, high performance but incompatible with some materials).

Hydraulic cylinders are designed in three basic versions. Single-acting cylinders have pressure on only one side of the piston, with the return movement provided by a spring or external force. They are mainly used in lifting devices and presses. Double-acting cylinders with a single-sided piston rod are most common in practice, where the force during extension $F_1 = pS_1$ is greater than the force during retraction $F_2 = p(S_1 - pis\ rod)$. The area ratio S_1/S_2 is typically 1,3 to 2:1, which means different forces and speeds in both directions of movement. Telescopic cylinders consist of a set of pistons of different diameters, allowing for a large stroke with a small overall dimension.

7.2 Compressibility of the medium as a fundamental difference between systems

The difference in compressibility is perhaps the most important physical parameter distinguishing pneumatic systems from hydraulic systems. Air at a typical working pressure of 6 bar has an adiabatic bulk modulus of approximately 8.4 bar, while hydraulic oil at 50°C reaches a value of approximately 15,000 bar. This enormous difference, roughly a factor of 1800:1, fundamentally determines the behavior of both systems under load and their suitability for different applications. The compressibility of air increases with pressure according to the relationship $B = \gamma \cdot P$ (where $\gamma = 1.4$ for air), meaning that at 10 bar, air has a bulk modulus of only 14 bar – still vastly lower than that of oil.

The positioning accuracy of pneumatic and hydraulic systems directly reflects this difference in compressibility. A standard pneumatic cylinder without advanced feedback typically achieves an accuracy of only ±1 to ±5 mm, with the air acting as a spring that compresses under load. A simple calculation illustrates this effect: a Ø50 mm cylinder with a 200 mm stroke at 6 bar has a chamber volume of approximately 393,000 mm^3. A load of 100 N creates an additional pressure $\Delta P =$ 0,051 bar, which, with a bulk modulus of 8,4 bar, results in a volume change of 2,385 mm^3, corresponding to a piston displacement of 1,2 mm. In comparison, the same hydraulic cylinder at 200 bar under the same load ($\Delta P = 0{,}51$ bar) would move only 0.007 mm (7 µm), a difference of approximately 170:1.

Modern servo-pneumatic systems can significantly improve positioning accuracy through a closed-loop control using proportional valves and position sensors. Advanced solutions, such as the Festo Motion Terminal, achieve repeatability of ±0,01 mm (10 µm), which approaches the performance of standard hydraulic systems. However, these results come at the cost of significantly higher system complexity, the need for continuous position measurement, and active compensation for air compressibility. A basic pneumatic system without electrical feedback can never reach this level of accuracy due to the inherent elasticity of the medium.

Hydraulic systems, in contrast, achieve high accuracy naturally due to the rigidity of the fluid. The stiffness of a hydraulic system can be calculated using the formula:

$$K = \frac{E \times A^2}{V}$$

where:

E is the bulk modulus of the fluid,

A is the piston area,

V is the oil volume.

A critical observation is that stiffness increases with the square of the piston area but is inversely proportional to the fluid volume in the system. This explains why minimizing the volume between the valve and the actuator is essential for achieving high dynamic response. Standard hydraulic proportional systems typically achieve accuracies of ±0,1 to ±1 mm, while electrohydraulic servo systems equipped with LVDT or magnetostrictive sensors can achieve accuracies better than ±0,001 mm (1 µm), with the most precise applications achieving sub-micrometer resolution.

The effect of temperature on compressibility is a significant and often overlooked factor. An increase in hydraulic oil temperature by 56°C (100°F) reduces the bulk modulus to approximately 61 % of its original value, corresponding to a drop from 15,000 bar to roughly 9,150 bar. When combined with as little as 1% air content in the

oil, a temperature increase of 56°C can reduce the bulk modulus by up to 67% compared to ideal conditions. Therefore, professional hydraulic systems require effective cooling and thorough venting to maintain the expected stiffness and stability.
The transmission of pressure changes in a system illustrates the practical consequences of compressibility. The speed of sound in hydraulic oil is approximately 1300-1500 m/s, meaning that in a 10 m long pipe, pressure changes are transmitted in about 7-8 ms – a delay that is practically negligible. In contrast, a pneumatic system must first compress the air in the chamber before the load can begin moving, resulting in measurable delays and potential instability, particularly in high-frequency applications. Research indicates that a system operating at 3,000 psi (207 bar) and 3,8 GPM requires up to 6,75 hp of power solely to compress air at a frequency of 100 Hz, demonstrating that such a system cannot operate efficiently at this frequency due to energy losses from air compressibility.

7.3 Working pressures, forces, and their consequences for system design

Working pressures clearly distinguish the application areas of pneumatics and hydraulics. Pneumatic systems typically operate at 6-8 bar (87-116 psi), with a maximum pressure usually limited to 10-12 bar due to safety considerations, compressor efficiency, and component lifespan. Some specialized applications use pressures up to 20,7 bar (300 psi), but these are rare. In contrast, hydraulic systems are classified according to ISO 4413 as low pressure (up to 70 bar), medium pressure (70-210 bar, common in industrial applications), high pressure (210-350 bar), and very high pressure (350-700 bar for specialized applications). This classification reflects the robustness required of components to operate safely under the specified pressures.

Force calculations highlight the practical implications of these pressure differences. Using the basic formula $F = p \times A$, a Ø50 mm pneumatic cylinder (area 1963 mm^2) at 6 bar generates a force of 1,178 kN (approximately 120 kg). The same cylinder at a hydraulic pressure of 200 bar produces a force of 39,3 kN (approximately 4007 kg), 33 times greater than the pneumatic force. To achieve the same 39,3 kN using pneumatics, a cylinder would require a diameter of Ø290 mm, which is impractical for most applications. This mathematical reality explains why hydraulics dominate in scenarios requiring high forces within compact dimensions.

Power density is a critical parameter for mobile applications and devices with limited installation space. Hydraulic systems offer very high power density, whereas pneumatic systems provide relatively low power density. A practical example illustrates the difference: to generate a force of 10 kN, a pneumatic cylinder operating at 6 bar requires a diameter of Ø146 mm and weighs approximately 6,8 kg, while a hydraulic cylinder operating at 200 bar needs only a diameter of Ø25 mm and weighs about 1,4 kg. This represents a 5,8× difference in diameter and a 4,9× difference in weight. Such factors become crucial in mobile machinery, aerospace systems, and any application where space and weight are limited.

The impact on component dimensions and costs is direct. Catalog data shows that a Festo DNC Ø125 mm pneumatic cylinder has a base weight of 6,8 kg and produces a force of 7.4 kN at 6 bar. In contrast, a Parker HMI Ø50 mm hydraulic cylinder weighs just 3,7 kg and produces 41,2 kN at 210 bar – delivering 5,6 times more force at roughly half the weight. For heavy-duty applications, this difference becomes even more pronounced. Since catalog prices correlate strongly with component size, a more compact hydraulic solution is often cheaper overall, despite its higher cost per unit of power.

The difference between the effective piston area and the nominal area is an important technical consideration. For compressive force (piston extension), the effective area corresponds to the full piston area $\pi D^2/4$. For tensile force (piston retraction), however, the effective area is reduced by the cross-sectional area of the piston rod and is given by

$$\frac{\pi(D^2 - d^2)}{4},$$

where:

$d$is the diameter of the piston rod.

As an example, a cylinder with a 100 mm piston diameter and a 45 mm piston rod has a tensile area that is approximately 20,2% smaller, resulting in a proportional reduction in force at the same pressure. This asymmetry in performance must be taken into account when dimensioning hydraulic or pneumatic systems.

7.4 Dynamic characteristics – speed, response, and steering precision

Pneumatic systems excel in movement speed, typically achieving 0,1 to 1,5 m/s, with maximum values reaching up to 2 m/s in special applications. The low density of air and its rapid expansion enable very dynamic motion characteristics. Test measurements show average speeds of approximately 0,35 m/s during extension and 0,37 m/s during retraction for an unloaded cylinder. For speeds above 1 m/s, the use of lubricated compressed air is recommended to extend seal lifetime.

Hydraulic systems are generally slower, typically reaching 0,01 to 0,5 m/s with standard sealing technology. The maximum recommended speed for conventional seals is around 1 m/s (3,28 ft/s). Special high-speed applications such as injection molding machines can achieve 1-1.5 m/s, while extreme cases – such as high-performance casting machines – may reach 4-8 m/s, but only with specially designed high-performance seals.

The dynamic response of the systems shows an interesting comparison. Pneumatic valves react faster – direct-acting solenoid valves have a response time of approximately 30 ms, while pilot-operated valves range from 100 to 1000 ms. Hydraulic servo valves, however, achieve impressive dynamic characteristics: conventional nozzle-flapper servo valves have a frequency response of 100-200 Hz at a phase shift of –90°, while high-speed linear servo valves reach 400-450 Hz with a step response of only 2-12 ms. Standard proportional hydraulic valves achieve 20-40 Hz, and high-performance types reach 40-70 Hz. Pneumatic proportional valves with piezo technology (such as the Festo VTEM) achieve high frequency response while reducing energy consumption by up to 95% compared to conventional solenoid valves.

Control accuracy is an area where fundamental differences become apparent. A standard pneumatic cylinder without position feedback achieves an accuracy of only ±several millimeters, which is unsuitable for precision applications. Servo-pneumatic systems with a closed-loop controller and proportional valves can achieve an accuracy of ±0,01 mm (Festo Controlled Pneumatics), but at the cost of high system complexity and continuous active regulation. Standard hydraulic proportional systems naturally achieve an accuracy of ±0,1 to ±1 mm without the need for advanced electronics. Hydraulic servo systems equipped with LVDT or magnetostrictive sensors routinely achieve an accuracy of ±0,01 mm, and in the most demanding applications with an integrator in the control loop, resolution below 10 nanometers (0,00001 mm) can be achieved.

Position repeatability is a key parameter in industrial applications. Basic pneumatic systems typically achieve repeatability in the range of ±0,1 to ±1 mm, whereas servo-pneumatic systems with proportional valves reach repeatability of approximately ±0,25% of the commanded position. Hydraulic proportional valves exhibit hysteresis of 1-5% and repeatability better than 1%, while hydraulic servo valves achieve hysteresis below 1% and repeatability better than 0,5%. For robotic or precision-motion applications requiring very high repeatability, hydraulic servo systems are often the only technologically feasible solution.

Speed control in pneumatic systems is traditionally implemented using throttle valves with one-way restriction (meter-in or meter-out). Modern proportional pneumatic systems with piezoelectric valves can achieve closed-loop speed control accuracy of around ±0,25%. Hydraulic flow-control valves offer significantly more precise regulation due to the much lower compressibility of hydraulic fluid. Proportional hydraulic valves reach linearity of approximately ±1-3%, while servo valves achieve ±0,5% linearity with excellent repeatability across the entire load range. Load variation strongly affects speed in pneumatic systems because of air compressibility, whereas closed-loop hydraulic servo systems automatically compensate for load changes and maintain constant speed.

7.5 Energy efficiency and its economic implications

Overall energy efficiency is one of the most significant differences between pneumatic and hydraulic systems, with direct economic consequences. Pneumatic systems reach an overall efficiency of only 10-30% (typically around 20-23%), while hydraulic systems commonly achieve 40-60%, and in optimized conditions operational efficiencies of 85-90% are possible. In practical terms, producing 1 HP of mechanical power with a pneumatic actuator requires approximately 7-8 HP of electrical input for the compressor, whereas a hydraulic system needs only 2-3 HP.

A detailed breakdown of losses within the pneumatic system illustrates where the inefficiencies arise. Electric motors operate with efficiencies of 80-96%, with smaller motors (< 10 kW) typically showing lower values. Compressors, however, are the major source of loss:

- small compressors (< 10 kW): 35-50% efficiency
- medium compressors (10-100 kW): 40-60%
- large compressors (> 100 kW): 51-73%
- centrifugal compressors (the most efficient): ~59.9-63.4%
- piston compressors (least efficient): ~39.6-73.1%

Air treatment units (filters, dryers) consume 10-15% of the total energy. System leaks are a critical issue: a well-maintained system loses < 10%, an average system loses 20-30%, and poorly maintained installations may lose 40-50%. According to the U.S. Department of Energy, roughly 30% of all compressed air is wasted through leakage. The final actuator – the pneumatic cylinder – has an efficiency of just 10-35%, with roughly half of the input energy being discarded into the atmosphere as unused expansion energy.

The hydraulic power chain has a significantly more favorable efficiency profile than its pneumatic counterpart. The electric motor (85-92%) drives a hydraulic pump with an efficiency between 80-95%, depending on the pump type: gear pumps 75-80%, vane pumps 80-85%, axial piston pumps 85-95%, and radial piston pumps up to 92-95%. Distribution losses in hydraulic lines are typically only 2-5%. The final actuator – whether a hydraulic cylinder or hydraulic motor – reaches efficiencies of 85-92%. The multiplicative product of these efficiencies yields a total system efficiency of approximately 51-85%, which is two to three times higher than that of pneumatic systems.

A concrete example published by *Fluid Power World* illustrates this efficiency chain: a 10 HP electric motor (85%) delivers 8.5 HP to the shaft; a gear pump operating at 75% efficiency converts this to 6,4 HP of hydraulic power; a hydraulic motor at 80% efficiency then outputs 5,1 HP of mechanical power. The overall system efficiency is thus 51%.

The economic impact of leaks in compressed air systems is especially alarming. A single leak the size of a 6 mm hole at 7 bar results in a loss of 7,1 L/s of air – costing more than £10,500 per year at average electricity prices and generating approximately 15 tons of CO_2. In U.S. units, a 1/4 inch (6.35 mm) leak at 100 psi causes a leakage rate of 26,1 CFM, which equates to approximately $11,735 per year at an electricity cost of $0.07/kWh. According to the U.S. Department of Energy, industrial facilities lose around 30% of their compressed air production through leaks.

Using ultrasonic leak detectors – especially during nighttime when ambient noise is low – and repairing leaks systematically can save industrial plants tens of thousands of dollars annually.

Hydraulic systems have a clear advantage in the field of energy recovery, whereas pneumatic systems are practically unable to recuperate energy. Hydraulic accumulators achieve recovery efficiencies of 73-87.7%, offer power densities in the range of 10,000-1,000,000 W/kg, and provide extremely fast dynamic response. Practical applications demonstrate substantial benefits: hydraulic lifting platforms recover approximately 73% of gravitational potential energy during the downward stroke; hydraulic excavators achieve a 39-50% improvement in overall efficiency; wheel loaders show energy recovery potential in the range of 32-66%; and hydraulic hybrid drivetrains in automotive applications deliver fuel savings of around 25%. In contrast, pneumatic systems have no commercially viable technology for efficient energy recovery. Roughly 50% of the supplied pneumatic energy is lost directly to the atmosphere as unused expansion energy.

Various factors influence overall energy efficiency and must be considered during system optimization. Duty cycle has a major impact on pneumatic systems: increasing the duty cycle from 50% to 80% raises energy consumption by approximately 60%. Hydraulic systems are significantly less sensitive to changes in duty cycle. Idle time is particularly problematic for compressors – fixed-speed units operating in load/unload mode consume 20–35% of their rated energy even when no compressed air is produced, and transient switching losses can account for up to 20% of total energy use. Compressors equipped with variable-speed drives (VSD) virtually eliminate these losses and typically provide energy savings of up to 35%. Correct sizing is essential: every 2 psi increase in operating pressure increases compressor consumption by 1%, while oversized piping causes a loss of 15 psi, which increases consumption by 7%.

7.6 Safety and environmental aspects of both technologies

The risk of fire and explosion clearly favors pneumatic systems. Compressed air is a non-flammable medium, which makes pneumatic components inherently safe for use in ATEX zones (zones 1, 2, 20, 21, and 22 according to Directive 2014/34/EU). Mineral hydraulic oils, by contrast, typically have a flash point of 200-250°C and an auto-ignition temperature of 260-400°C, most commonly around 360°C. At high system pressures, a hydraulic leak can generate a fine aerosol capable of ignition, creating a serious fire hazard. In hazardous environments, this risk is mitigated by the use of fire-resistant HFD fluids in accordance with ISO 6743-4. HFC fluids are water-glycol mixtures with 35-50% water, commonly used in steelworks and foundries. HFDU fluids are synthetic esters with a flash point of 250-260°C and auto-ignition at 300-400°C, offering excellent performance but at 2-3 times higher cost. HFA fluids are oil-in-water emulsions with approximately 95% water and minimal lubricating capacity, while HFB fluids are water-in-oil emulsions containing 40-50% water, providing a balanced compromise of properties.

Leaks and environmental contamination represent another fundamental difference between the two technologies. Pneumatic leaks – although extremely costly in terms of energy consumption, typically accounting for 20-30% of production – are environmentally harmless, as the leaked medium is simply clean compressed air returning to the atmosphere. Hydraulic leaks, however, pose a severe environmental threat. A single liter of hydraulic oil can contaminate up to 1,000,000 liters of water. Mineral hydraulic oils are toxic to aquatic life, can cause respiratory distress in fish, persist in ecosystems for years, and the additives they contain tend to bioaccumulate across the food chain. Under the U.S. Clean Water Act, any hydraulic spill must be reported to authorities and followed by costly remediation procedures. EU Directive 2008/98/EC classifies waste oils as hazardous waste (EWC code 16 01 07) requiring regulated disposal at high cost.

Application cleanliness is critical in the food, pharmaceutical, and electronics industries. Pneumatics is ideal for food & beverage, pharmaceutical, and cleanroom applications where product contamination is unacceptable. ISO 14644-1 defines cleanroom classes: ISO 5 (the cleanest, 3,520 particles ≥ 0.5 μm/m^3) for aseptic filling and sterile products, ISO 6 for semiconductors, ISO 7 (most common, 352,000 particles) for packaging and assembly, and ISO 8 for basic cleanliness. GMP pharmaceutical grades correspond to these classes: Grade A equals ISO 5 for aseptic filling, Grade B equals ISO 5 at rest/ISO 7 in operation, Grade C equals ISO 7/8, and Grade D equals ISO 8. Hydraulic systems carry the risk of product contamination with oil and are therefore unsuitable for sterile environments. Food-grade hydraulic fluids with NSF H1 certification (ISO 21469:2006) are available, but they are more expensive and still pose a contamination risk.

The disposal of used media further highlights the contrast between the two systems. Compressed air does not require disposal and carries no associated costs or regulatory burdens. Hydraulic oil, on the other hand, requires costly and strictly regulated disposal, with EU regulations favoring regeneration over incineration. Disposal costs depend on both volume and contamination level. Biodegradable hydraulic fluids according to ISO 15380 significantly reduce environmental risk. HETG fluids are based on vegetable oils, offering more than 70% biodegradability in 28 days but lower oxidative stability. HEES fluids, made from synthetic esters, provide over 60% biodegradability with excellent technical and environmental properties; although they are 2-3 times more expensive, they reduce total cost of ownership when accounting for environmental risks and potential insurance savings. HEPG fluids, based on polyglycols, offer high performance but are incompatible with certain paints and seals.

Noise has a significant impact on the working environment. Pneumatic systems produce high sound levels, with air discharge reaching 80-115 dB(A), pneumatic tools 90-110 dB(A), and pneumatic drills averaging 114-116 dB(A), with peaks up to 130 dB(A). Compressors contribute 85-95 dB(A). Noise reduction can be achieved using exhaust silencers, which typically lower sound levels by 15-30 dB. Hydraulic systems are generally quieter, with pumps producing 60-90 dB(A) (typically 70-82 dB(A)) and hydraulic drills generating 85-107 dB(A). Sources of hydraulic noise include fluid-borne noise from pressure pulsations, structure-borne noise from vibrations, and acoustic amplification in the tank. Noise mitigation measures include hydraulic dampers (reducing noise by 5-8 dB), vibration isolation, and acoustic covers. According to EU Directive 2003/10/EC, the absolute exposure limit including hearing protection is 87 dB(A) LEX,8h, the upper limit requiring mandatory protection is 85 dB(A), and the lower limit for information and training is 80 dB(A).

7.7 Life cycle economics and maintenance strategies

The initial investment costs generally favor pneumatic cylinders. Pneumatic cylinders are 25-50% cheaper than hydraulic cylinders of the same size because they operate at lower pressures (80-150 psi) and can use less expensive materials such as aluminum and plastics. Hydraulic components, by contrast, must withstand pressures of 1,500-10,000 psi and require robust materials and precision machining. In many industrial facilities, a compressed air system is already available, whereas a complete hydraulic unit – including pump, tank, filters, cooler, and valves – can be two to three times more expensive. For simple applications requiring low forces, pneumatics is therefore more economically attractive.

Considering the cost of the working medium provides a longer-term perspective. Air is essentially free as a raw material, but approximately 76% of the lifetime cost of a compressor comes from electricity used for compression. Leaks can account for up to 30% of production (U.S. DOE), representing a significant hidden cost. Hydraulic oil, on the other hand, has an initial cost – mineral oils are the baseline, synthetics are two to three times more expensive, and biodegradable oils can be up to six times more costly. It also requires regular replacement and expensive disposal. In well-maintained systems, leaks are minimal (< 2%), but poorly maintained systems can experience 5-10% loss through leaks.

Energy operating costs are a decisive factor in system selection. A detailed study by Tolomatic (2014) comparing pneumatic and electric actuators highlights significant differences. For a 0.1 kW application operating at a 50% duty cycle, the annual operating cost of a pneumatic actuator is $476, compared to $345 for an electric actuator, resulting in savings of $131 per year. At an 80% duty cycle, pneumatic costs rise to $756/year versus $546/year for electric actuators, increasing savings to $210 annually. For a larger 0.5 kW application, these savings are even more pronounced, ranging from $655 to $1,050 per year. In large-scale applications, energy costs dominate: a 200 HP compressor operating 6,800 hours per year at 85% load consumes $144,840 worth of electricity annually ($0.12/kWh), with energy representing roughly 88% of the compressor's total ten-year life cycle cost.

Maintenance costs differ in both structure and frequency. Pneumatic systems generally incur lower costs per maintenance task – such as replacing seals or filters – but require more frequent attention, including daily drainage, weekly inspections, and monthly filter replacement. Hydraulic systems involve higher-cost tasks, including oil changes, specialized seals, and fine filtration, but require them less frequently, such as quarterly oil analysis and annual full maintenance. A critical finding is that up to 25% of hydraulic system failures are attributable to insufficient maintenance.

TCO (Total Cost of Ownership) analyses over the life cycle reveal some surprising results. Cost breakdown typically shows initial investment accounting for 10-15%, energy costs dominating at 70-76%, maintenance 10-15%, and replacements or repairs 5-10%. A case study in the food industry for noodle cutting demonstrates this clearly: a pneumatic system costs $4,441 over three years (with $3,960 attributed to maintenance), while an electric system costs only $1,524 over the same period, yielding a 66% savings and a return on investment of just 13 months. In automotive spot welding, pneumatic systems cost $3,750 over three years, compared to $1,750 for electric servo systems, making pneumatics twice as expensive. A Kistler study further showed that electromechanical systems save 77% of energy compared to hydraulics and 90% compared to pneumatics, with hydraulic systems consuming 4.4 times more energy than electromechanics and pneumatics up to 10 times more.

Component service life significantly affects long-term costs. Pneumatic cylinders typically achieve 3-5 million cycles, with premium models reaching up to 10 million cycles. At typical operating frequencies, this corresponds to a service life of 5-10 years. Factors influencing pneumatic cylinder life include air quality (contamination and humidity), operating frequency, temperature (optimal -20 to +80°C), side loads, and seal quality. Hydraulic cylinders generally have longer service lives, ranging from 10 to 20 years. For example, in heavy mining equipment, the mean time between failures (MTBF) is approximately 6,967 hours. The optimal preventive maintenance interval is about 3,500 hours; waiting until MTBF is reached could result in 55% of cylinders failing. Preventive maintenance can extend service life by 30-50%.

Downtime costs are often underestimated. Fortune Global 500 companies lose approximately $1.5 trillion annually due to unplanned outages, averaging $129 million per facility per year. Hourly downtime costs: automotive industry >$2 million/hour (50% increase since 2019), oil and gas ~$500k/hour (100% increase in 2 years), offshore production $38 million per year. In mining, 37% of outages are caused by hydraulic hose failures. Overall, 20% of all industrial outages are related to hydraulic problems. Repair speed (MTTR): tires typically 1-4 hours (easier replacement), hydraulics 3-8 hours (more complex, expertise required). Preventive maintenance costs 2-5 times less than reactive maintenance and reduces downtime by 36%.

7.8 A systematic approach to selecting the right system for the application

The choice between pneumatic and hydraulic systems must be based on a systematic evaluation of the application requirements across multiple criteria. The most important single factor is the required force. Pneumatic systems are suitable and economically advantageous for forces below 5 kN (approximately 500 kg) at pressures of 80-150 psi. For forces above 20 kN, hydraulic systems are almost inevitable, as pneumatic cylinders would need to be disproportionately large. The intermediate range of 5-20 kN depends on additional factors such as accuracy, speed, and cleanliness.

Environmental cleanliness is often a decisive factor. In the food industry (requiring ISO 21469 food-grade), pharmaceutical manufacturing (GMP Grades A-D, cleanroom ISO 5-8), and the electronics industry, pneumatic systems are preferred or even mandatory due to the risk of contamination from hydraulic oil. Food-grade hydraulics with NSF H1 certification are possible, but more expensive and still carry a contamination risk that most manufacturers are unwilling to accept. In explosive atmospheres, such as ATEX zones, pneumatic systems are inherently safer because air is non-flammable.

Accuracy and speed illustrate the trade-off between pneumatic and hydraulic systems. Pneumatics achieves high speeds (up to 2 m/s), but standard accuracy is only ±1-5 mm. Servo-pneumatics can reach ±0,01 mm, but this comes at the cost of high system complexity and increased expense. Hydraulic systems naturally achieve ±0,1-1 mm accuracy, while hydraulic servo systems routinely reach ±0,01 mm, with sub-micrometer resolution in the most demanding applications. For precise positioning, CNC machines, robots, and measurement devices, hydraulics or electromechanical systems are preferred.

Power density is critical for mobile applications. Construction machinery (bulldozers, excavators), mobile cranes, ships, and aerospace technology almost exclusively use hydraulics due to their ability to generate enormous forces (100+ kN) in compact dimensions at pressures exceeding 10,000 psi. Pneumatics would require impractically large cylinder sizes. Conversely, for desktop applications and stationary equipment, compactness is less critical, and pneumatics or electromechanical solutions may be sufficient.

Energy efficiency and total cost of ownership (TCO) are crucial for long-term economic evaluation. For applications with a high duty cycle (greater than 50% active time), pneumatic systems are very expensive due to their low overall efficiency of 10-30%. Hydraulic systems, with efficiencies of 40-60%, or electromechanical systems, with efficiencies of 70-80%, typically achieve a return on investment (ROI) within 12-36 months. For applications with a low duty cycle (less than 30%), pneumatic systems can be economically advantageous due to their lower initial costs. Energy costs account for 70-76% of the total life cycle costs, making efficiency a decisive factor.

Hybrid solutions and electromechanical alternatives represent modern trends. Hydropneumatic systems combine compressed air with a hydraulic pump, enabling fuel savings of up to 30% and energy regeneration during braking in hybrid buses and construction machinery. Electromechanical servo drives (2-40 Nm, 24 V/230 V AC) offer the highest precision and full position control, replacing pneumatics in HVAC dampers, valves, and robotic applications. Smart pneumatic systems with IoT connectivity enable real-time monitoring of pressure and flow, predictive maintenance using AI, and integration with PLCs, IO-Link, and CAN-bus. The trend is clear: electromechanical systems are increasingly replacing pneumatics where energy savings and precision justify higher initial costs.

A decision matrix with weighted evaluation helps to systematize the selection of actuation systems. Criteria are scored on a scale of 1-10, with weights assigned according to importance: power/performance [20%] – pneumatic 4, hydraulic 10, electromechanical 6; speed [15%] – pneumatic 10, hydraulic 5, electromechanical 8; accuracy [15%] – pneumatic 4, hydraulic 9, electromechanical 10; cost [15%] – pneumatic 9, hydraulic 4, electromechanical 6; cleanliness [15%] – pneumatic 10, hydraulic 3, electromechanical 8; energy efficiency [10%] – pneumatic 3, hydraulic 8, electromechanical 9; ecology [5%] – pneumatic 10, hydraulic 4, electromechanical 8;

flexibility [5%] – pneumatic 8, hydraulic 7, electromechanical 10. The weighted overall scores are: pneumatic 6,95, hydraulic 6,80, electromechanical 7,75. This result reflects the modern trend toward electromechanical solutions wherever technically and economically feasible.

Practical application areas clearly show the strengths of each system. Pneumatics dominates in the food industry (packaging, filling, sorting), pharmaceuticals (ISO 7-8 cleanrooms, sterile production), assembly lines (pick-and-place systems, robotics), the automotive industry (pneumatic tools, paint shops), and cleanroom environments (electronics, laboratories). Hydraulics is preferred in construction (bulldozers, excavators, cranes operating at pressures over 10,000 psi), heavy industry (presses, metalworking machinery), mining (elevators, heavy manipulators), CNC machines (precise positioning), aviation (landing gear, rudders), and mobile machinery (trucks, ships).

A systematic comparison of hydraulic and pneumatic systems shows that there is no universally superior system; rather, the suitability depends on the specific application requirements. Hydraulics excel in applications requiring high forces (greater than 20 kN), high precision (±0.01 mm), compact power density, and high energy efficiency (40-60%). The extremely low compressibility of hydraulic oil – approximately 10,000 times lower than that of air – ensures rigidity, stability under load, and the ability to hold positions without continuous energy input. Pneumatics, on the other hand, dominate in applications where cleanliness (food, pharmaceutical), high speed (up to 2 m/s), operational simplicity, and safety in explosive atmospheres are critical. Electromechanical alternatives are increasingly replacing both systems where the highest precision and energy efficiency justify the higher initial costs.

Key quantifiable factors for decision-making include the following: bulk modulus of hydraulic oil 15,000 bar versus air 1,4 bar (ratio 10,000:1); force at the same cylinder diameter, hydraulics vs. pneumatics = 33:1; accuracy, hydraulic ±0.01-1 mm vs. pneumatic ±1-5 mm; speed, pneumatic 0,1-2 m/s vs. hydraulic 0,01-0.5 m/s; overall energy efficiency, hydraulics 40-60% vs. pneumatics 10-30%; leakage, pneumatic 20-30% vs. hydraulics < 2%; service life, hydraulics 10-20 years vs. pneumatics 5-10 years; energy costs, 70-76% of total cost of ownership. Biodegradable HEES hydraulic fluids (over 60% biodegradability in 28 days) and smart IoT-enabled predictive maintenance systems represent the future of both technologies.

Modern industrial systems often combine multiple technologies. Hybrid systems leverage the advantages of each technology for different parts of the machine – hydraulics for main power drives, pneumatics for auxiliary fast movements, and electromechanics for precise positioning. The decision requires a multi-criteria evaluation with an emphasis on total cost of ownership (TCO) over 10-20 years, not just the initial price. A successful mechatronics engineer must master all three technologies and understand their physical principles, strengths, limitations, and economic implications for the optimal design of modern automation systems.

8 MOTION CONTROL AND COMMUNICATION

Motion control is a fundamental area of mechatronics, responsible for ensuring precise and coordinated movement in automated systems. From simple linear motions in pneumatic cylinders to complex multi-axis trajectories in robotic applications, motion control technologies directly influence the quality, productivity, and flexibility of modern manufacturing processes. This chapter provides a systematic overview of the basic principles of motion control systems, with particular emphasis on their integration with industrial communication protocols that enable the coordination of individual components into fully functional units.

Over the past decades, industrial automation has evolved from isolated control units to interconnected systems that communicate in real time and share information across the entire production infrastructure. Modern motion control systems must therefore not only execute precise movements but also interface seamlessly with higher-level control systems, sensor networks, and other automation elements. Understanding these interactions is essential for the effective design and implementation of contemporary mechatronic systems.

8.1 What is motion control?

Motion control is a discipline that ensures the control of the position, speed, and acceleration of mechanical systems over time. It is a specialized field of automation that combines knowledge from mechanics, electrical engineering, control engineering, and computer science. The basic goal of motion control is to accurately and repetitively move an object from its starting position to its target position with defined speed and time parameters.

(principle of operation)

A motion control system is composed of several fundamental components that operate together within a closed control loop. The motion controller generates reference signals for the actuators based on the desired motion trajectory. The driver handles the power stage, converting the controller's signals into suitable power outputs for the actuator. The actuator, which may be an electric motor, pneumatic cylinder, or hydraulic cylinder, performs the actual mechanical movement. Position and speed sensors provide continuous feedback on the system's state, allowing precise control and real-time correction of deviations.

The control loop operates on the principle of feedback. The controller continuously compares the desired position, velocity, and acceleration with the actual values measured by the sensors. Based on any deviation, it calculates corrective actions to minimize the difference between the target and actual states. The overall quality of control depends on the dynamic characteristics of the mechanical system, the accuracy of the sensors, the performance capabilities of the actuators, and the sophistication of the control algorithms.

Motion control systems find applications across a broad spectrum of industries. In CNC machine tools, they provide precise guidance of cutting tools along programmed paths with micrometer-level accuracy. Industrial robots rely on motion control to coordinate the movement of multiple joints, enabling complex handling, assembly, and processing tasks. Automated production lines use motion control to synchronize the operation of conveyors, manipulators, and workstations, ensuring smooth and efficient throughput. Packaging and labeling machines require precise timing and movement coordination to match production speed. In laboratory instruments, such as micropositioners and scanning devices, motion control enables nanometer-scale positioning and high-resolution scanning (Fig. 67).

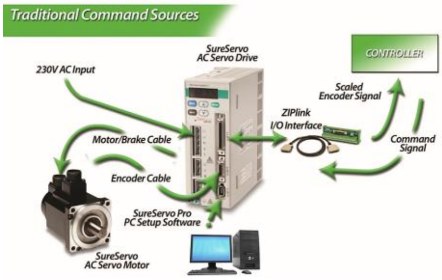

Fig. 67 Motion control diagram

The fundamental requirements for motion control systems include positioning accuracy, repeatability, dynamic response, control stability, and energy efficiency. Positioning accuracy defines the maximum deviation between the actual and desired end positions. Repeatability measures the system's ability to return to the same position during repeated movements. Dynamic response reflects how quickly the system reacts to changes in reference signals and its ability to track rapid motions. Control stability ensures the system reaches the desired position without oscillation or divergence. Energy efficiency is particularly important in applications with high-frequency movements or long transport paths.

Choosing the appropriate actuation technology depends on the specific application requirements. Electric servo drives are preferred for applications demanding high precision, fast dynamics, and flexible control. Stepper motors are suitable for simpler applications with lower dynamic requirements where feedback is not needed. Pneumatic systems are used for fast movements where lower positioning accuracy is acceptable, such as in pick-and-place operations. Hydraulic systems are ideal for applications requiring high forces or torques at relatively slow speeds.

8.2 Point-to-point vs. contour control

Motion control systems can be categorized based on how they manage the movement trajectory between start and end positions. This classification into point-to-point and contour control reflects fundamental differences in application requirements and system complexity.

Point-to-point control, also called PTP (point-to-point) (Fig. 68), is the simplest type of motion control. In this mode, the system moves an object from the initial position to the target position without strictly defining the trajectory between them. The main concerns are reaching the end position accurately and completing the movement within an acceptable time. The intermediate trajectory can be optimized for speed, energy efficiency, or mechanical load, regardless of whether it follows a straight or direct path.

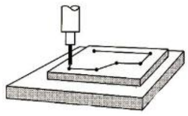

Fig. 68 Point to point control

Typical applications of point-to-point control include pick-and-place operations in automated assembly lines, where a component must be transferred from a feeder to an assembly position. The exact trajectory of the movement is not critical; what matters is that the component is accurately placed at the target position. Similarly, in product palletizing, a robot arranges items on a pallet according to a predefined pattern, and the motion between placement positions can follow any path. Drilling and tapping operations on CNC machines also represent point-to-point applications, where the tool must reach the precise drilling location, but the path taken to get there is not important.
(principle of operation)
Contour control, also called continuous path (CP) control, requires precise following of a specified trajectory in space. The system must ensure that the actuator passes through all designated points along the trajectory at defined speeds and accuracy, while deviations are continuously monitored and minimized. This type of control demands higher computational power and more sophisticated control algorithms from the controller.
Contour control is crucial in applications where the trajectory itself determines the quality of the result. Laser cutting requires exact guidance of the laser beam along the part's contour at a constant feed rate to maintain consistent cut quality. CNC milling of complex shapes, such as molds and dies, demands precise three-dimensional contour tracking with micrometer-level tolerances. Plasma and waterjet cutting share similar trajectory requirements. Robots applying adhesives or sealants also rely on contour control to move the nozzle along a predefined path with controlled speed, ensuring uniform coating thickness.
(principle of operation)
Contour control uses interpolation to generate a continuous trajectory between defined points. Linear interpolation creates straight segments between successive points, suitable for geometric shapes with straight edges. Circular interpolation allows precise creation of circular arcs specified by a center, radius, or three points, which is essential for machining curved features. Helical interpolation combines circular motion in one plane with linear motion in the perpendicular direction, typically used for thread cutting. Cubic spline interpolation ensures smooth transitions between points with continuity in velocity and acceleration, which is important for high-speed machining, where abrupt changes in direction can cause vibrations and reduce surface quality.

The choice between point-to-point and contour control strongly influences the hardware and software demands of a motion control system. Point-to-point (PTP) control can be implemented with a simpler controller and lower computing power because the system does not need to continuously calculate or correct the motion trajectory. A basic position loop with a simple velocity profile generator is sufficient. In contrast, contour (CP) control requires a more powerful controller capable of continuously calculating interpolated trajectory points, predicting upcoming segments to ensure smooth transitions, and controlling multiple axes simultaneously with precise synchronization. Control loop sampling frequencies are typically higher, often ranging from several kilohertz to tens of kilohertz.
Hybrid strategies leverage the advantages of both approaches. A system can perform fast PTP movements for relocating between work areas and switch to contour control during actual processing tasks. This optimizes overall cycle time while maintaining required quality. Modern motion controllers often support both modes, allowing seamless switching based on the application requirements.

8.3 Speed profiles – Trapezoidal profile

The speed profile describes how the velocity of a motion varies over time between the start and target positions. Choosing an appropriate speed profile is crucial because it directly affects system dynamics, mechanical stress on components, positioning accuracy, and overall cycle time. The most commonly used profile in motion control applications is the trapezoidal speed profile.
The trapezoidal profile consists of three phases: a constant acceleration phase at the start, a constant velocity phase in the middle, and a constant deceleration phase at the end. Its name comes from the shape of the velocity-time curve, which resembles a trapezoid. If the distance to be traveled is too short to reach the maximum velocity, the profile becomes triangular, with no constant velocity phase; the system transitions directly from acceleration to deceleration.
The trapezoidal profile can be described mathematically in terms of its three basic phases (Fig. 69).

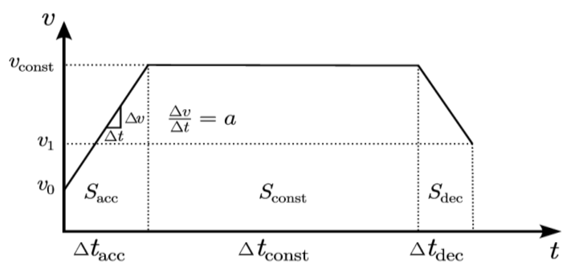

Fig. 69 Trapezoidal speed profile

In the acceleration phase, which lasts from time t =0 to $t = t_a$, the following relationship applies to the velocity:

$$v_{(t)} = at$$

where:

a is constant acceleration and t is time.
The following applies to the position in this phase:

$$s_{(t)} = \left(\frac{1}{2}\right) at^2$$

In the constant-velocity phase, which lasts from time $t = t_a$to $t = t_a + t_v$, the velocity remains constant.

$$v_{(t)} = v_{max} = at_a$$

and the position changes linearly:

$$s_{(t)} = s_a + v_{max}(t - t_a)$$

where:
s_a is the position reached at the end of the acceleration phase.
In the deceleration phase, which lasts from time $t = t_a + t_v$ to $t = t_a + t_v + t_d$, the following relationship holds:

$$v_{(t)} = v_{max} - a(t - t_a - t_v)$$

For simplicity, it is often assumed that the deceleration has the same magnitude as the acceleration, that is, $t_d = t_a$.
The parameters of the trapezoidal profile are calculated based on the required travel distance, the maximum velocity, and the maximum acceleration. For a motion over a distance s with maximum velocity v_max and acceleration a, the following relationship holds:
Acceleration and deceleration time:

$$t_a = t_d = \frac{v_{max}}{a}$$

Trajectory during acceleration and deceleration:

$$s_a = s_d = \left(\frac{1}{2}\right)\left(\frac{v_{max}^2}{a}\right) = \left(\frac{1}{2}\right) at_a^2$$

Total distance during acceleration and deceleration phases:

$$s_{ad} = s_a + s_d = \frac{v_{max}^2}{a}$$

If the total required distance s is greater than s_{ad}, the profile includes a constant-velocity phase:

$$s_v = s - s_{ad}$$

$$t_v = \frac{s_v}{v_{max}}$$

Total movement time:

$$t_{total} = t_a + t_v + t_d = 2 \cdot t_a + t_v$$

If the required distance is smaller than s_ad, the maximum velocity is not reached and the profile takes a triangular shape. In this case, the actual peak velocity v_{peak} is calculated from the following relationship:

$$v_{peak} = \sqrt{}(a \times s)$$

and the total movement time is:

$$t_{total} = 2\sqrt{}(s/a)$$

The main advantage of the trapezoidal profile is its simple implementation and minimal computational requirements. The algorithm used to generate the profile is straightforward and can be easily implemented even in basic motion controllers. The profile also ensures energy-efficient use of the constant-velocity phase, during which no continuous energy input is required for acceleration. For many applications without demanding requirements for extremely smooth motion, the trapezoidal profile provides sufficient control quality.

A significant disadvantage of the trapezoidal profile is the theoretically infinite jerk (the rate of change of acceleration) that occurs at the transition points between phases. At the start of the acceleration phase, the acceleration changes abruptly from zero to the value a, which theoretically corresponds to an infinite jerk. Similarly, at the end of the acceleration phase, the acceleration drops instantaneously from a back to zero. These abrupt changes introduce mechanical shocks transmitted through the drive into the mechanical structure. The result is vibration, noise, increased mechanical stress on components, and reduced positioning accuracy.

In real systems, sudden changes in acceleration are physically impossible due to system inertia and the finite stiffness of mechanical connections. The actual acceleration changes only at a finite rate, which is determined by the dynamic properties of the drive and the mechanical design. This discrepancy between the ideal trapezoidal profile and the actual motion can lead to overshoot, oscillations, and reduced positioning accuracy. For applications with higher dynamic and accuracy requirements, it is therefore more appropriate to use velocity profiles with limited jerk, such as the S-curve profile.

Despite its limitations, the trapezoidal profile remains widely used in industrial practice. It is suitable for applications with relatively low dynamic demands, where simplicity and fast computation are the key priorities. Typical examples include slower transport systems, low-cycle pick-and-place operations, positioning tasks with modest accuracy requirements, and systems with high mechanical stiffness where vibration is not a critical factor.

8.4 Speed profiles – S-curve profile

The S-curve speed profile represents an advanced approach to motion control that addresses the main shortcomings of the trapezoidal profile. The key principle of the S-curve profile is the limitation of jerk – the time derivative of acceleration – to a finite value, thereby eliminating abrupt changes in acceleration and significantly reducing mechanical shocks and vibrations (Fig. 70).

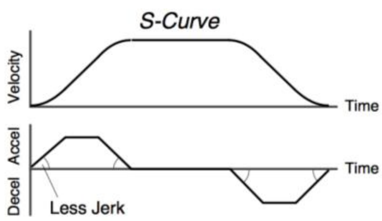

Fig. 70 S-curve speed profile

The name “S-curve profile” comes from the characteristic shape of the acceleration curve over time, which resembles the letter S. This shape is achieved by a gradual increase in acceleration from zero to the maximum value, followed by a gradual decrease back to zero. The velocity curve also exhibits a smoother progression, with gradual changes in slope rather than the sharp breaks typical of the trapezoidal profile.

The S-curve profile can be divided into seven phases. The first phase represents an increase in jerk from zero to the maximum value j_max, resulting in a gradual increase in acceleration. In the second phase, the acceleration remains constant at the maximum value a_max, similar to the trapezoidal profile. The third phase involves a decrease in jerk back to zero, leading to a gradual reduction in acceleration. The fourth phase is a period of constant maximum velocity v_max. Phases five through seven mirror the first three phases, but with negative signs, ensuring smooth deceleration.

The mathematical description of the S-curve profile is more complex than that of the trapezoidal profile. For the first phase (increase in jerk), the following relationship applies:

$$j_{(t)} = j_{max}$$
$$a_{(t)} = j_{max} \times t$$
$$v_{(t)} = \left(\frac{1}{2}\right) j_{max} t^2$$
$$s_{(t)} = \left(\frac{1}{6}\right) j_{max} t^2$$

where:

j_{max} is the maximum allowed jerk.

For the second phase (constant acceleration):

$$j_{(t)} = 0$$
$$a_{(t)} = a_{max}$$
$$v_{(t)} = v_1 + a_{max} \times (t - t_1)$$

where:

v_1 and t_1 are the velocity and time values at the end of the first phase.

Similar relationships apply to the subsequent phases, with the appropriate signs and initial conditions.

The key parameter of the S-curve profile is the perceptual jerk, often expressed as a percentage of the total acceleration time. Typical values range from 10% to 50%. Lower values result in smoother motion with longer transition phases, whereas higher values produce a motion profile approaching a trapezoidal shape. The selection of an appropriate jerk value depends on the mechanical properties of the system, the required cycle speed, and the acceptable level of vibration.

The advantages of the S-curve profile are particularly pronounced in applications with higher dynamic demands. Limiting jerk significantly reduces mechanical shocks at the start and end of motion, which decreases mechanical stress on components and extends their service life. The reduction of mechanical resonance excitation lowers structural vibrations, improving positioning accuracy and surface quality in machining operations. Smoother motion also reduces system noise and enhances operator comfort. In applications involving the transport of liquids or bulk materials, spillage is minimized.

The disadvantages of the S-curve profile stem from its increased computational complexity, which requires a more powerful motion controller. The algorithms for generating the S-curve profile are more complex and demand a greater number of real-time computational operations. The total movement time is slightly longer than with a trapezoidal profile due to the transition phases associated with jerk, given the same speed and acceleration limits. For simple applications with low dynamic requirements, using an S-curve profile may be uneconomical.

Modern motion controllers often implement S-curve profiles with configurable jerk parameters. Users can optimize the profile for a specific application by setting the maximum jerk, acceleration, and velocity. Some advanced systems support adaptive S-curve profiles that automatically adjust parameters based on detected load, vibration, or other operating conditions. There are also modified versions of S-curve profiles, such as asymmetric S-curves with different parameters for acceleration and deceleration, or multi-segment S-curves designed for complex motion sequences.

The practical implementation of the S-curve profile requires careful parameter tuning. The maximum jerk is typically selected based on the mechanical properties of the system and the desired proportion of transition phases. Too low a jerk results in unnecessarily long transition phases and reduced productivity, whereas too high a jerk produces a motion profile approaching a trapezoidal shape, thereby losing the advantages of smooth motion. Experimental tuning, with monitoring of vibration and positioning accuracy, is often necessary to achieve optimal performance.

S-curve profiles are now standard in high-precision CNC machine tools, where vibrations directly affect the quality of the machined surface. In robotics, S-curve profiles are used to ensure smooth movements when handling fragile objects. High-speed pick-and-place systems employ S-curve profiles to minimize mechanical shocks at high cycle frequencies. Laboratory and measuring instruments rely on S-curve profiles to eliminate vibrations that could compromise measurement accuracy.

8.5 Multi-axis coordination

Multi-axis coordination extends motion control principles to systems with multiple simultaneously controlled axes. While controlling a single axis is relatively straightforward, coordinating multiple axes introduces additional challenges in synchronization, trajectory interpolation, and motion optimization. Modern applications in robotics, CNC machine tools, and automated manufacturing systems require precise and synchronized control of two to ten or more axes simultaneously.

The fundamental requirement for multi-axis coordination is the synchronization of all axes so that they reach their target positions at the same time and at coordinated speeds. This necessitates that the motion controller calculates speed profiles for each axis individually, taking into account the different paths each axis must traverse. If one

axis must travel a longer path than the others, its maximum speed must be correspondingly higher so that all axes complete their movements simultaneously.
In linear interpolation for multi-axis systems, the end effector moves along a straight line in Cartesian coordinates. The motion controller calculates speed profiles for each axis so that the ratio of axis velocities corresponds to the ratio of the distances each axis must travel. For motion from point $P_1(x_1, y_1, z_1)$ to point $P_2(x_2, y_2, z_2)$, the total distance is first calculated:

$$L = \sqrt{[(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2]}$$

Then, a normalized motion parameter u is defined in the range from 0 to 1, which changes over time according to the selected speed profile. The positions of the individual axes over time are:

$$x_{(u)} = x_1 + u(x_2 - x_1)$$
$$y_{(u)} = y_1 + u(y_2 - y_1)$$
$$z_{(u)} = z_1 + u(z_2 - z_1)$$

Circular interpolation allows the creation of circular arcs in a plane defined either by three points or by a center and a radius. For an arc in the XY plane defined by the center (x_c, y_c), radius R, initial angle θ_1, and final angle θ_2, the following relationship applies:

$$x_{(\theta)} = x_c + R \cdot cos(\theta)$$
$$y_{(\theta)} = y_c + R \cdot sin(\theta)$$

The angle θ changes from θ_1 to θ_2 according to a time course defined by the velocity profile.
Advanced applications use NURBS (Non-Uniform Rational B-Splines) interpolation to generate complex, smooth trajectories. NURBS curves are defined by control points and provide accurate representations of free-form shapes with second-order continuity (C2), meaning continuity not only in position and direction but also in curvature. This is critical for high-speed machining, where discontinuities in curvature can cause changes in acceleration and induce vibrations.

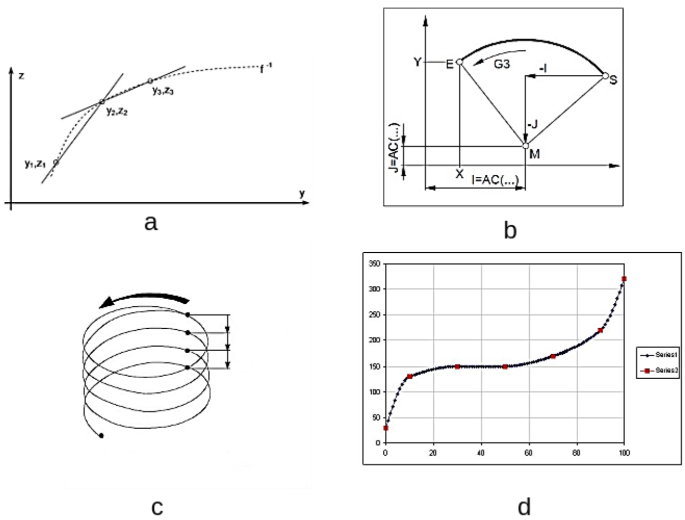

Fig. 71 Types of interpolation
a – linear, b – circular, c – helical, d – spline

Synchronization of multiple axes requires precise timing of control signals. Typical motion controllers operate at sampling frequencies ranging from 1 to 20 kHz, generating new position commands every 50 μs to 1 ms. Even higher frequencies may be necessary for precise contouring operations. Jitter in timing between axes must be minimized, typically below 1 μs, to ensure trajectory accuracy.

Modern approaches to multi-axis coordination include cross-coupled control, in which the system monitors not only individual axis deviations but also deviations from the desired contour. For example, if one axis moves slower than the others, the controller detects this as a contour deviation and applies corrective actions to minimize it, rather than correcting individual positions alone. This approach significantly enhances contour tracking accuracy at high speeds.

Electronic line shafting (ELS) is a specialized application of multi-axis coordination in which multiple axes are synchronized to a virtual or physical master axis. This technique is used in packaging, printing, and textile machines, where multiple processes must be coordinated with the production speed. The master axis defines the base frequency, and the slave axes follow it with a specified gear ratio and phase shift. Modern motion controllers support dynamic changes of gear ratios and phase shifts during operation, enabling flexible adaptation of the production process.

Another critical aspect of multi-axis coordination is the optimization of feed rates with respect to the kinematic and dynamic limits of all axes. Feed rate optimization ensures that no axis exceeds its maximum speed, acceleration, or jerk during coordinated motion. Feed rate optimization algorithms typically operate in two phases: the forward-looking phase predicts future segments of the trajectory and identifies sections where speed must be reduced due to sharp turns or axis limits; the backward-propagation phase adjusts speeds in preceding segments so that the calculated deceleration can be achieved without violating any limits.

In robotic applications, multi-axis coordination extends to the control of joint variables, which are transformed into Cartesian positions and orientations of the end effector using forward kinematics. Inverse kinematics addresses the opposite problem: it calculates the required joint angles for a desired position and orientation of the end effector. In 6-axis robots, inverse kinematics is often ambiguous, with multiple possible solutions. The controller must select the optimal solution while considering mechanical limits, singularities, and minimization of joint movements.

Challenges in multi-axis coordination include handling singularities – configurations in which control over certain degrees of freedom is lost. Near singularities, even small changes in the end effector's position can require extremely high joint speeds. Modern robust algorithms detect proximity to singularities and adjust the trajectory or reduce speed to prevent problems. Another challenge is the optimization of computation time: complex algorithms for feed rate optimization and cross-coupled control can demand significant computing power, which must be available in real time.

8.6 Fundamentals of Industrial Communication Protocols

Modern motion control systems are not isolated units but are integrated components of complex automation systems. Communication between motion controllers, drives, sensors, PLCs, and higher-level control systems is enabled by industrial communication protocols. The choice of an appropriate communication protocol significantly affects the performance, reliability, and cost of the entire system.

Industrial communication protocols can be classified according to several criteria. Based on the physical layer, protocols can be divided into serial protocols (RS-232, RS-485, CAN) and Ethernet-based protocols (EtherNet/IP, EtherCAT, PROFINET). Considering the determinism of communication, protocols can be classified as deterministic, with guaranteed timing parameters suitable for motion control, or non-deterministic, more appropriate for data communication and monitoring. According to network topology, protocols can follow master-slave architectures with central control or peer-to-peer architectures with equal participants.

Basic requirements for communication protocols in motion control include deterministic communication with guaranteed maximum latencies, typically in the millisecond or microsecond range. Time-base synchronization is critical for accurate timing of control actions in distributed systems. Low communication latency, ideally below 1 ms, enables high-frequency data exchange between the controller and drives. High throughput is necessary for transmitting position commands, feedback, and diagnostic data. Immunity to electromagnetic interference ensures reliable communication in industrial environments with significant electrical noise (Fig. 72).

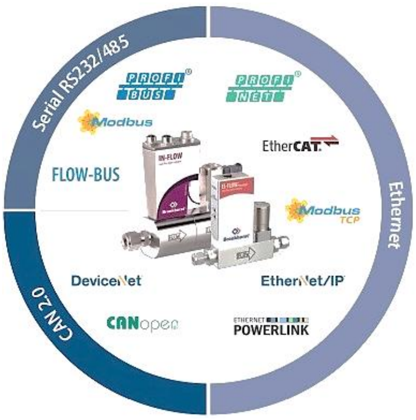

Fig. 72 Communication protocols

Ethernet-based protocols use standard Ethernet hardware, offering advantages in component availability and the existing knowledge base. Standard IEEE 802.3 Ethernet provides high throughput (typically 100 Mbit/s to 1 Gbit/s) but is not deterministic. Media access is controlled by CSMA/CD (Carrier Sense Multiple Access with Collision Detection), which can cause unpredictable delays under high network load. For motion control applications, modifications to Ethernet have been developed to ensure deterministic communication.

These modifications typically involve changes to the MAC layer to guarantee deterministic media access. Some protocols employ time slicing, dividing the communication cycle into time slots allocated to individual devices. Others implement priority mechanisms, ensuring that critical messages have guaranteed access to the medium. Clock synchronization between devices ensures accurate communication timing, typically with an accuracy better than 1 μs.

Network topology significantly affects communication performance and reliability. A star topology with a central switch is easy to implement but introduces a single point of failure. A ring topology allows redundancy and automatic communication recovery if one connection is interrupted. A linear (daisy-chain) topology minimizes cabling but is more susceptible to outages. Modern systems often combine different network topologies to optimize cost, reliability, and performance. Communication protocols can also be classified according to the communication model. The client-server model, in which the client initiates communication and the server responds, is suitable for non-critical data exchanges. The producer-consumer (publish-subscribe) model enables efficient distribution of data from a single producer to multiple consumers without requiring multiple point-to-point connections. The cyclic model, with regular data exchange at defined intervals, is typical for motion control, where the controller periodically sends position commands and receives feedback.

The choice of an appropriate communication protocol depends on the specific requirements of the application. Protocols such as EtherCAT or SERCOS are suitable for high-performance motion control with sub-millisecond cycles. For integrated systems with devices from multiple vendors, PROFINET or EtherNet/IP, with broad vendor support, may be more advantageous. For cost-sensitive applications with lower dynamic requirements, Modbus TCP may be sufficient. Hybrid solutions combine different protocols at different levels of the automation hierarchy – for example, EtherCAT for the motion control level, PROFINET for the process control level, and Ethernet TCP/IP for the supervisory level

8.7 Basic industrial protocols – overview

Modbus is one of the oldest and most widely used industrial communication protocols. It was developed by Modicon in 1979, originally for communication with PLCs over serial lines. Modbus employs a simple master-slave architecture, in which the master device initiates communication and the slave devices respond. The protocol supports up to 247 slave devices on a single bus. Communication follows a request-response principle, where the master sends a request and waits for a response from the addressed slave device.

Modbus defines several physical implementations. Modbus RTU (Remote Terminal Unit) uses serial communication via RS-485 with binary data encoding and CRC checking. Modbus ASCII also uses serial communication, but with ASCII encoding and LRC checking. Modbus TCP/IP encapsulates Modbus messages in TCP/IP packets, enabling communication over Ethernet. Each message contains the address of the slave device, a function code (e.g., read coils, write registers), a data field, and a checksum (Fig. 73).

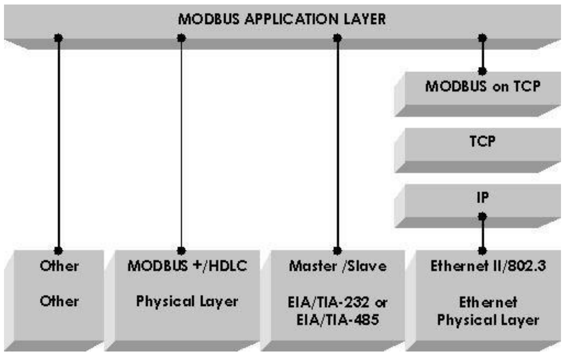

Fig. 73 MODBUS protocol

The advantages of the Modbus protocol lie in its simplicity and widespread support. The specification is open and freely available, which has contributed to its broad adoption in industry. Implementation is relatively simple and low-cost, and the protocol is supported by nearly all automation technology manufacturers. Disadvantages include limited communication speed, particularly in serial implementations, the lack of advanced diagnostic functions, and insufficient support for complex data structures.

EtherCAT (Ethernet for Control Automation Technology) is a high-performance industrial Ethernet protocol developed by Beckhoff Automation in 2003. EtherCAT achieves extremely low cycle times, typically between 100 μs and 1 ms, making it ideal for demanding motion control applications. A key innovation is the "on-the-fly" data processing method, in which each device reads and writes relevant data directly from the passing Ethernet frame without stopping to process the entire frame (Fig. 74).

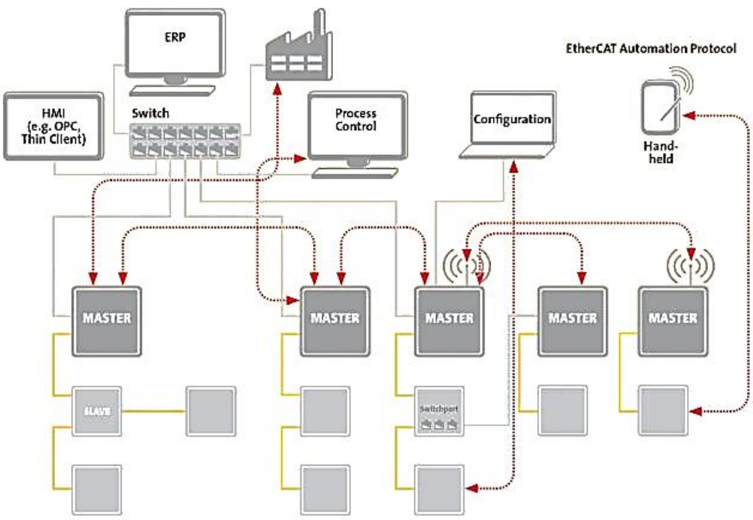

Fig. 74 EtherCAT protocol

Mbit/s. The master device sends a frame that passes through all slave devices arranged in a line topology. Each slave device is equipped with an ASIC chip capable of reading and writing its data during the passage of the frame, with a delay of only a few nanoseconds. The frame then returns to the master, enabling error detection and network status monitoring. This principle allows data exchange with thousands of I/O points in sub-millisecond cycles. Synchronization in an EtherCAT network is achieved using the Distributed Clocks mechanism, which synchronizes the clocks of all devices with an accuracy better than 1 μs. This is critical for applications requiring precise synchronization of multiple drives, such as multi-axis CNC machines or robots. EtherCAT supports various application profiles, including CANopen over EtherCAT (CoE) and Safety over EtherCAT (FSoE) for the integration of safety functions.

PROFINET (Process Field Network) is an industrial Ethernet protocol developed by the PROFIBUS & PROFINET International (PI) consortium under the leadership of Siemens. PROFINET exists in several versions that differ in their real-time communication capabilities. PROFINET IO (Input/Output) is the standard version for typical automation tasks, with cycle times typically ranging from 10 to 100 ms. PROFINET RT (Real-Time) provides deterministic communication with cycle times of approximately 1 to 10 ms, making it suitable for modern control applications. PROFINET IRT (Isochronous Real-Time) achieves cycle times below 1 ms with jitter less than 1 μs, which is essential for motion control applications (Fig. 75).

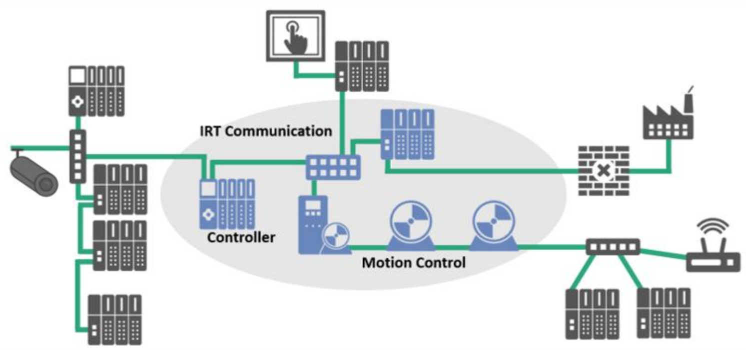

Fig. 75 ProfiNET protocol

PROFINET IRT uses time slicing, in which the communication cycle is divided into time slots. Time-critical data is transmitted in reserved slots with the highest priority, while standard TCP/IP communication occupies the remaining slots. This approach ensures the coexistence of real-time and non-real-time communication on the same physical network. PROFINET supports various topologies, including star, ring, and linear, with integrated switches in devices.

PROFINET is closely integrated with the Siemens TIA Portal (Totally Integrated Automation) ecosystem, simplifying system configuration, programming, and diagnostics. The protocol provides extensive diagnostic functions, including device identification, status monitoring, alarms, and maintenance information. PROFINET Safety enables the transmission of safety signals over the same physical network without requiring a separate safety infrastructure.

EtherNet/IP (Ethernet Industrial Protocol) is an industrial Ethernet protocol based on CIP (Common Industrial Protocol). CIP is an application layer protocol originally developed for DeviceNet and ControlNet. EtherNet/IP adapts CIP for use over standard Ethernet and TCP/UDP. The protocol is managed by ODVA (Open DeviceNet Vendors Association) and is widely supported by manufacturers, particularly in North America (Fig. 76).

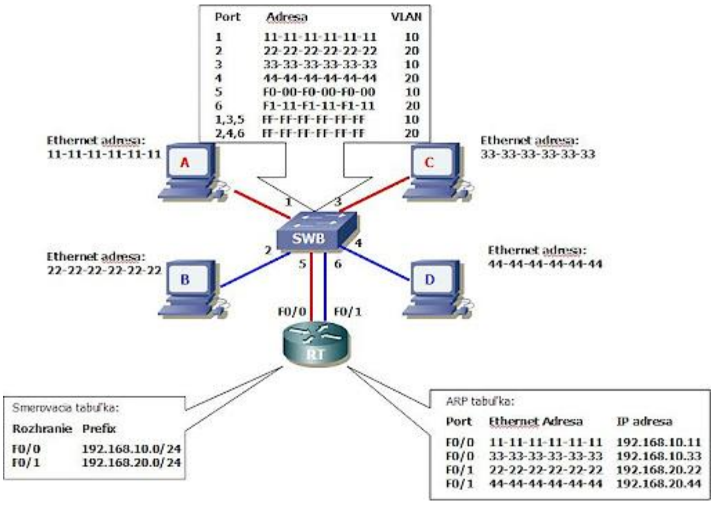

Fig. 76 Ethernet IP protocol

EtherNet/IP uses standard Ethernet hardware without any special modifications. The protocol supports two types of communication: explicit messages via TCP for aperiodic data exchange, configuration, and diagnostics, and implicit (I/O) messages via UDP for periodic process data exchange with lower overhead. Implicit messages follow a producer-consumer model, in which the producer device multicasts data and all interested consumer devices receive it without the need for point-to-point connections. EtherNet/IP cycle times typically range from 2 to 100 ms, making it suitable for many process and discrete automation applications, although this can be limiting for demanding motion control. The protocol offers advantages in flexibility, scalability, and integration with IT infrastructure, enabling industrial communication to coexist with normal IT traffic on a shared network.

The SERCOS (Serial Real-time Communication System) interface, specified in IEC 61491, was originally developed specifically for high-performance motion control applications. SERCOS III is the latest generation of the protocol based on Ethernet technology. It achieves extremely short cycle times (typically 31,25 μs, 62,5 μs, or 1 ms) with jitter below 1 μs, making it ideal for highly dynamic multi-axis applications. SERCOS III employs a time-slicing approach with a dual-channel architecture. The real-time channel transmits time-critical motion data in reserved time slots, while the non-real-time channel uses the remaining bandwidth for TCP/IP communication, diagnostics, and configuration. A ring topology with redundant paths ensures high reliability; if one connection is interrupted, communication automatically switches to the backup path.

Selecting the appropriate protocol requires an analysis of the specific application requirements. For high-end motion control with nanosecond-level jitter, SERCOS III is the optimal choice. EtherCAT offers excellent performance at lower cost and with broad vendor support. PROFINET is advantageous in environments dominated by Siemens technology and requiring integration with PROFIBUS devices. EtherNet/IP is suitable for flexible systems with diverse devices and IT integration needs. Modbus TCP remains relevant for simpler, cost-sensitive applications with lower dynamic requirements.

8.8 OPC UA – Industry 4.0 standard

OPC UA (OPC Unified Architecture) is a fundamental communication standard for Industry 4.0 and the Industrial Internet of Things (IIoT). Unlike protocols primarily focused on real-time control, OPC UA provides a comprehensive solution for semantic interoperability, secure communication, and integration of heterogeneous systems from the sensor level to cloud applications (Fig. 77).

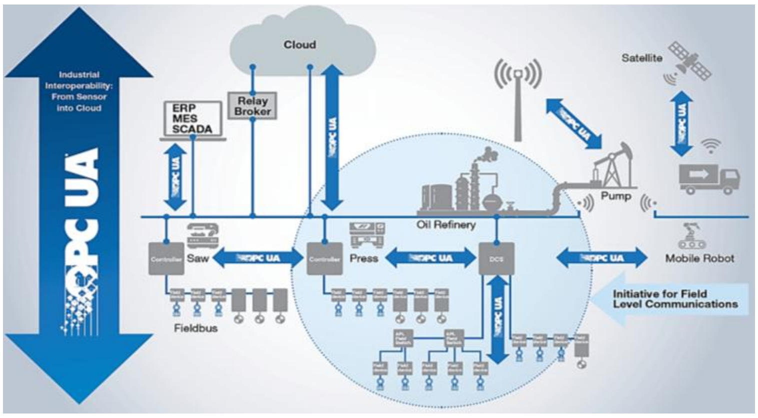

Fig. 77 OPC-UA

OPC (OLE for Process Control) was created in the mid-1990s in response to the need for a standardized approach to accessing process data from different devices and systems. The original OPC Classic was based on Microsoft COM/DCOM technology, which limited its usability primarily to Windows platforms and local networks. OPC UA was developed by the OPC Foundation as a platform-independent, secure, and extensible solution and was first published in 2008. In 2016, OPC UA was adopted as the international standard IEC 62541.

The OPC UA architecture is based on a service-oriented approach (SOA). The fundamental elements are OPC UA servers, which provide data and functionality, and OPC UA clients, which access these services. Communication can take place in two basic models. The Client–Server model is based on a request–response paradigm, where the client initiates requests to read, write, or call methods, and the server provides responses. The Publish–Subscribe model enables efficient distribution of data from publishers to multiple subscribers without the need for direct connections, which is advantageous for distributed systems and cloud applications.

A key innovative feature of OPC UA is its information model, which allows not only the transfer of data but also its semantic meaning. The OPC UA Address Space is a hierarchical structure of objects, variables, methods, and events that represent a device or system. Each element in the address space is identified by a NodeId, which

uniquely identifies the object within the server. Relationships between objects are defined by references that express different types of relationships such as hierarchy, inheritance, associations, and others.
OPC UA defines more than 25 basic data types, including primitive types (Boolean, Integer, Float), time types (DateTime, Duration), structured types (arrays, structures), and complex types. The extensibility mechanism allows the definition of custom data types and object models for specific application domains. This is the basis for the Companion Specifications, which define standardized information models for specific industrial sectors.
Companion Specifications extend the basic OPC UA standard with domain-specific models. Euromap 77 defines a standard for communication with injection molding machines. umati (universal machine tool interface) is an initiative by the German Machine Tool Builders' Association (VDW) for the standardization of machine interfaces. The VDMA Robotics Companion Specification defines a model for industrial robots. The PackML (Packaging Machine Language) Companion Specification defines standardized states and modes for packaging machines. These specifications ensure that devices from different manufacturers can communicate and be integrated without the need for proprietary adapters.
Security is a fundamental feature of the OPC UA architecture. The security model has three pillars: authentication ensures that the communication parties are who they claim to be, using X.509 certificates; authorization controls the access rights of users and applications to specific data and functions; and encryption protects communication against eavesdropping and data modification. OPC UA supports various security policies ranging from basic (None) for trusted networks to high (Basic256Sha256) for public networks and critical applications.
OPC UA supports multiple transport protocols. OPC UA TCP is a binary protocol optimized for low latency and high throughput, suitable for local networks. HTTPS enables firewall-friendly communication via web services, suitable for communication over the Internet. MQTT (Message Queuing Telemetry Transport) is a lightweight publish–subscribe protocol suitable for IoT applications with limited resources. AMQP (Advanced Message Queuing Protocol) is a standardized message-oriented protocol suitable for enterprise integration.
Time-Sensitive Networking (TSN) is a set of IEEE 802.1 standards that bring deterministic communication to standard Ethernet. OPC UA over TSN combines the rich information models of OPC UA with the deterministic timing guarantees of TSN, enabling the use of OPC UA for demanding real-time applications, including motion control. TSN mechanisms include time synchronization (IEEE 802.1AS) for synchronizing device clocks with accuracy better than 1 μs, time-aware scheduling (IEEE 802.1Qbv) for bandwidth reservation and guaranteed latency, and frame preemption (IEEE 802.1Qbu) for interrupting the transmission of non-critical frames with critical ones.
The integration of OPC UA with the Industry 4.0 concept is fundamental. The Reference Architecture Model Industry 4.0 (RAMI 4.0) defines a three-dimensional

model combining product lifecycle layers, automation hierarchy, and functional layers. OPC UA is located in the RAMI 4.0 communication layer and provides integration across the hierarchy from field devices through control systems to enterprise systems and the cloud. The Asset Administration Shell (AAS) is a virtual representation of a physical or logical asset that contains all relevant information about the asset, structured according to the RAMI 4.0 model. OPC UA is the primary technology for implementing AAS interoperability.

The Open Industry 4.0 Alliance is an initiative by manufacturers including ABB, Bosch, Siemens, and others to create open standards based on OPC UA. The Open Edge Computing (OEC) Guidelines define the architecture for edge computing in industrial applications. The Master Asset Model (MAM) provides a framework for structuring asset information. MQTT Message Bus integration enables efficient publish–subscribe communication in distributed systems.

Practical implementations of OPC UA cover a wide range of applications. In smart factories, OPC UA provides vertical integration from sensors and actuators through PLC and SCADA systems to ERP and MES systems. In predictive maintenance, OPC UA collects data on equipment condition, vibrations, temperatures, and other parameters, which are analyzed to predict failures. In digital twin applications, OPC UA provides real-time data from a physical object to its digital representation. In supply-chain integration, OPC UA enables communication between the production systems of different companies using standardized models.

The challenges of implementing OPC UA include the complexity of the standard, which requires considerable know-how to implement correctly. The computing resources required for full functionality can be limiting for small embedded devices. Certification and interoperability testing require investment in tools and processes. Migration from legacy systems to OPC UA can be complex and costly. Despite these challenges, OPC UA is now considered the de facto standard for Industry 4.0 integration, and its adoption continues to grow.

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