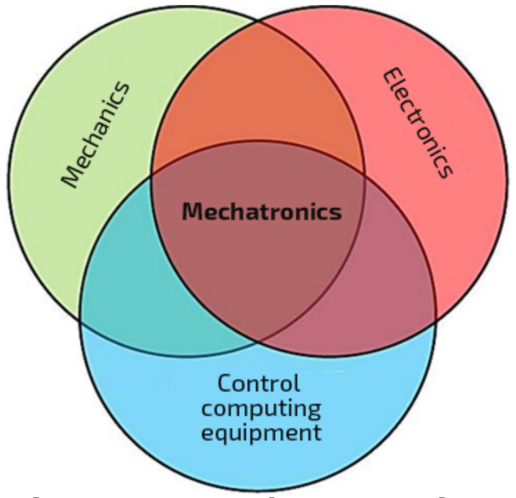
CONCEPT OF MECHATRONICS AS A FIELD OF SCIENCE AND TECHNOLOGY

Mechatronics is a branch of science and technology based on the synergistic integration of precision mechanics components with electronic, electrical engineering, and computer elements. This integration enables the design and production of qualitatively new mechanisms, machines, and systems with intelligent control of their functional movements.

Historical note: The term "Mechatronics" was introduced by the Yaskawa Electric company in 1969. It is derived from the combination of the words "MECHANICS" and "ELECTRONICS". This merging in a single term signifies the integration of knowledge in these fields of science and technology, which has created conditions for the emergence of new-generation equipment and the production of the latest types of devices.

In well-known definitions, the triune nature of mechatronic systems is emphasized, based on the idea of a deep interconnection between mechanical, electronic, and computer components.



Mechatronic system

Thus, the system integration of the three specified types of elements is a necessary condition for constructing a mechatronic system.

Mechatronics is a branch of science dedicated to analyzing the operational states of mechatronic objects and the functional interactions between mechanical, energy, and informational processes within them and with the external environment, as well as to the synthesis of mechatronic objects. On the other hand, mechatronics is a branch of technology that ensures the entire life cycle of a mechatronic object. A mechatronic object is synthesized through the synergistic integration of precision mechanical components with electronic, electrical engineering, and computer elements, enabling the design and production of qualitatively new modules, systems, and machines with intelligent control of their functional states (including movements).

The first level includes a mechatronic unit or mechatronic module. A mechatronic module is a standardized mechatronic object with autonomous documentation, usually designed to implement movements along a single coordinate. Examples of mechatronic modules include parts of machines—such as spindle heads, rotary tables. Modules can also be motors, gearboxes, etc. More complex modules (autonomous drives) include gear motors, wheel motors, spindle motors, drum motors, and rotary tables.

Basic knowledge
CONCEPT OF MECHATRONICS AS A FIELD OF SCIENCE AND TECHNOLOGY

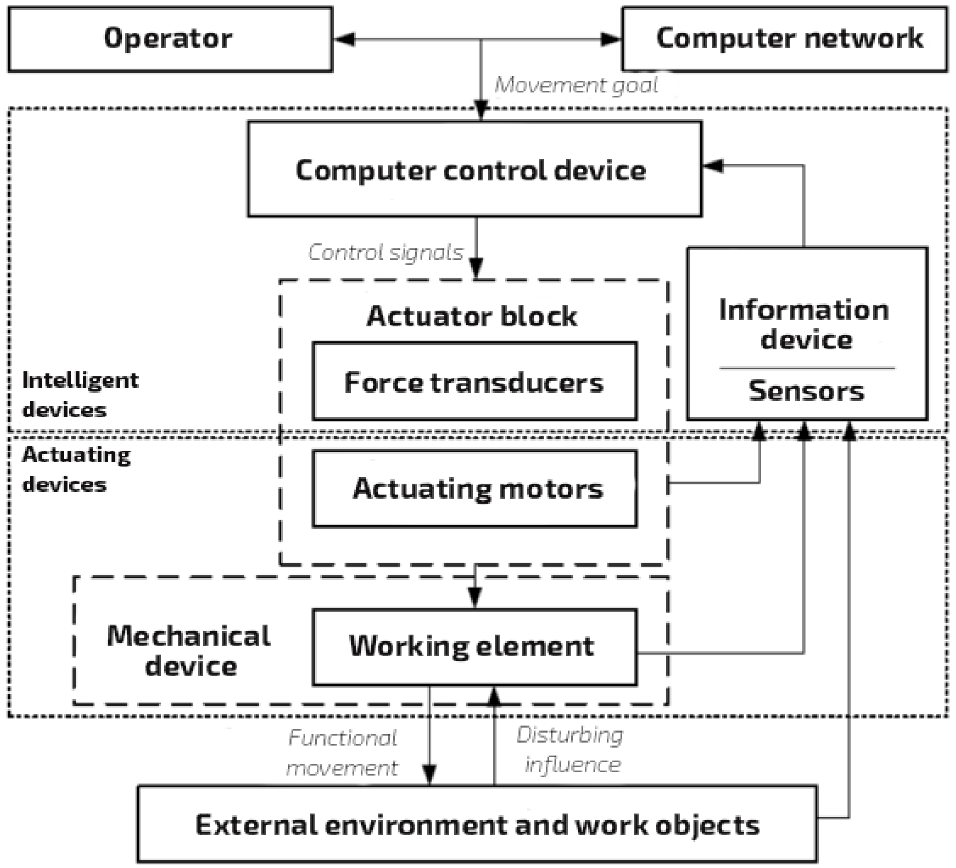
The second level is an assembly (machine) comprising several modules intended for executing specified movements under interaction with the external environment. Examples of assemblies include industrial robots, CNC machines, etc.

The third level is a mechatronic system consisting of several assemblies or an assembly and a series of separate modules, i.e., objects of the same or different lower levels.

Objects of varying degrees of mechatronic integration or levels include CNC machines, industrial and specialized robots, numerous samples of aerospace, military equipment, and automotive engineering. Office equipment (fax machines, copiers), computing devices (plotters, printers, disk drives), video equipment (VCRs), household appliances (washing machines, sewing machines, dishwashers, and other automatic machines), non-traditional transport (electric bicycles, freight carts, electric scooters, wheelchairs), pilot and operator training simulators, and the show business industry (sound and lighting systems) are also mechatronic.

Structure and principles of designing mechatronic systems

Figure presents a generalized structure of machines with computer control (automatic robots) used in machine building. This diagram illustrates the principles of designing mechatronic systems. The external environment for the machines of this class is the technological environment, which includes main and auxiliary equipment, technological tooling, and work objects. When the mechatronic system performs a specified functional movement, the work objects exert disturbing influences on the working element. Examples of such influences include cutting forces during machining operations, contact forces and moments during assembly, and the reaction force of a fluid jet during hydraulic cutting operations.



Generalized diagram of a machine with computer-controlled movement

Basic knowledge

STRUCTURE AND PRINCIPLES OF DESIGNING MECHATRONIC SYSTEMS

External environments are divided into two main classes: deterministic and non-deterministic. Deterministic environments are those for which the parameters of disturbing influences and the characteristics of work objects can be predetermined with the necessary accuracy for the design of mechatronic systems. Some environments are inherently non-deterministic (for example, extreme environments: underwater, underground, etc.). The characteristics of technological environments can typically be determined through analytical and experimental research methods, as well as computer modeling. For example, to determine cutting forces during machining, experimental studies are conducted on special setups, vibration impact parameters are measured on vibration test rigs, followed by the development of mathematical and/or computer models of the disturbing influences.

The primary characteristic of mechatronic systems is the presence of three mandatory parts — mechanical (electromechanical), electronic, and computer components — interconnected by energy and information flows:

- The electromechanical part includes mechanical links and transmissions, the working body, electric motors, sensors, and additional electrical elements (brakes, couplings).
- The mechanical device is designed to convert the movements of the links into the required movement of the working body.
- The electronic part consists of microelectronic devices, power transducers, and electronics for measurement circuits.
- Sensors are intended to collect data about the actual state of the external environment and work objects, the mechanical device, and the drive block, followed by initial processing and transmission of this information to the computer control device.
- Usually, the computer device includes the upper-level computer and control controllers for motion.

The computer control device performs the following main functions:

- Control of the mechanical movement process of the mechatronic module or multi-dimensional system in real time, with sensor data processing;
- Organization of control for the functional movements of the mechatronic system, which involves coordinating the control of mechanical movement and associated external processes;
- Interaction with the operator through an interface in autonomous programming mode (off-line) and directly during the movement of the mechatronic system (on-line);
- Organization of data exchange with peripheral devices, sensors, and other system devices.

The task of a mechatronic system is to convert input information received from the upper-level control into purposeful mechanical movement, with control based on the principle of feedback.

The feature of the mechatronic approach to design is the integration of two or more elements, possibly of different physical nature, into a single functional module.

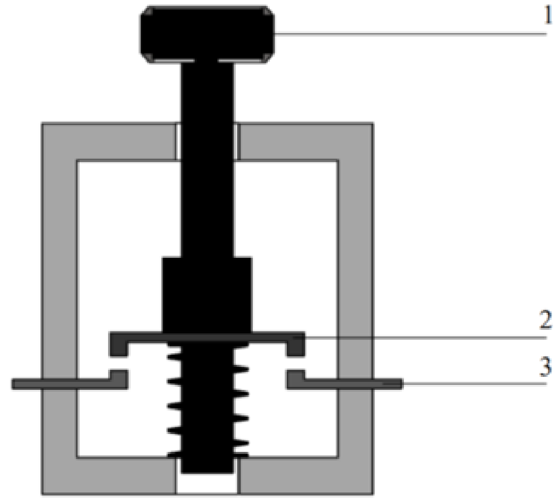
Basic knowledge

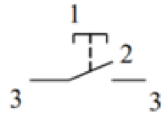
PRINCIPLE OF OPERATION AND DEVICE OF THE SWITCH

Principle of operation and device of the switch

Switches are used to start or break the current in an electrical circuit. Depending on the design, they can be push-button or latching.

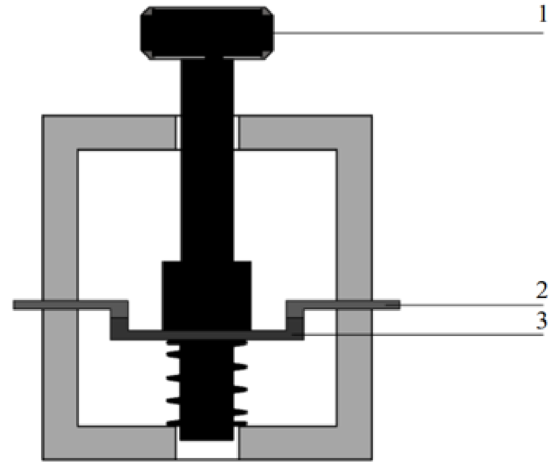
Normally open contacts.

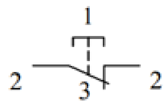




Cross-sectional image of the switch and designation of the NC (normally closed) contact.

Normally closed contacts.





Cross-sectional image of the switch and designation of the NC (normally closed) contact.

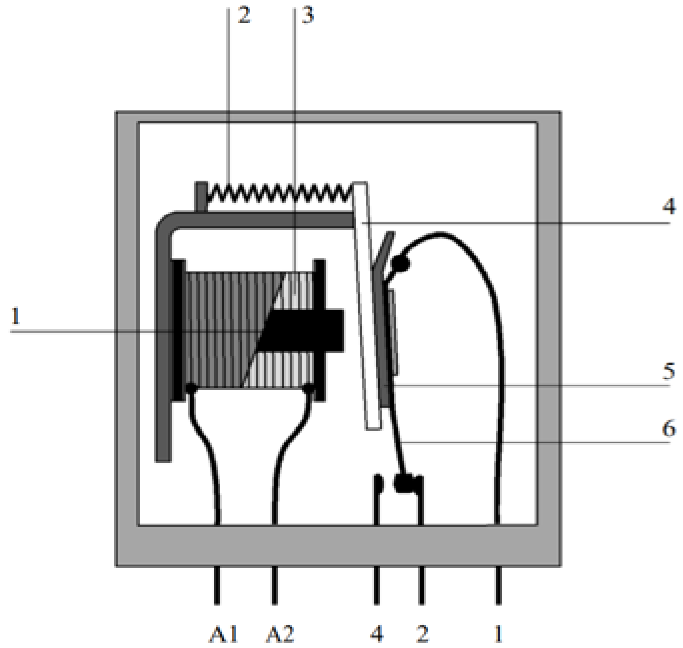
Relays and contactors

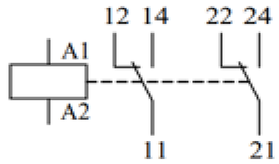
A relay is an electromechanical switch in which the control circuit is isolated from the controlled circuit. The relay consists of a coil with a metal core, an armature serving as the actuating element, a return spring, and switching contacts (see diagram). When voltage is applied to the coil, an electromagnetic field is generated. This causes the armature to be attracted to the core. The armature then acts on the relay contacts, which are either closed or open depending on the state. If the current flowing through the coil is interrupted, the spring returns the armature to its original position.

Relays are used in electropneumatic control systems for signal amplification, delay, and signal conversion, as well as for data merging and separating control and main circuits. They are also used in electrical control systems to isolate direct current (DC) and alternating current (AC) circuits.

Basic knowledge

RELAYS AND CONTACTORS





Cross-sectional view of the relay and its symbolic diagram

Components in a pneumatic control system and their functions

- **Compressor.** In pneumatic systems, energy is supplied by screw or piston compressors with an output pressure of 700–800 kPa (7-8 bar). This means that the minimum operating pressure without a regulator, created in the cylinder, will be equal to 600 kPa (6 bar), despite leaks and network losses.
- **Compressed air filters.** Filters are installed either centrally or decentrally in compressed air systems. They purify the air from condensate and dirt particles.
- **Pressure regulator.** In subsystems where pressure levels need to be monitored, regulators are installed. They compensate for fluctuations in the compressed air networks. The set pressure remains constant until the incoming pressure exceeds it by more than 50 kPa (0.5 bar).
- **On-off valves.** They separate different compressed air networks.
- **Distributors.** They stop the air flow and direct it to the working elements at the desired time.
- **Power distributor.** They match the diameter to the cylinder and supply the required amount of compressed air to it.
- **Cylinders.** Pneumatic cylinders are working elements with high durability and long service life. Standard sizes of cylinders can reach high speeds.
- **Single-acting cylinders.** In single-acting cylinders, air enters only from one side, where they have an inlet. This means they can only operate in one direction. Emptying occurs through a hole in the cylinder cap.

Cross-sectional image and schematic diagram of a single-acting cylinder

Basic knowledge

PRINCIPLE OF OPERATION AND DEVICE OF THE SWITCH

Double-acting cylinders. In double-acting cylinders, air enters from both sides, meaning they can operate in two directions.

In a double-acting cylinder, each pressure chamber has openings. Before switching in the opposite direction, the corresponding chamber (piston or rod) must be vented.

Image, sectional view, and schematic diagram of a double-acting cylinder

Speed regulation of double-acting cylinders

- Forward stroke (regulation of the outgoing flow): A throttle with a check valve is installed at the compressed air outlet (regulation of the outgoing flow). The outgoing air passes through the throttle. Usually, the speed regulation of double-acting cylinders is done this way. The speed control does not depend on the load.

- Forward stroke (regulation of the incoming flow): A throttle with a check valve is placed at the compressed air inlet (regulation of the incoming flow). Speed regulation is only possible during the forward stroke. Small changes in load on the piston rod cause large fluctuations in moving speed. The load in the direction of the cylinder movement increases above the set value. This method is not suitable for cylinders installed vertically.

- Forward and reverse strokes: The compressed air outlet is regulated using a throttle. The speed can be set separately for forward and reverse strokes.

- Purpose and features of pneumatic distributors: Pneumatic distributors control the direction of compressed air movement. The flow direction is indicated by an arrow. Activation can be manual, mechanical, pneumatic, or electrical. In automated systems, usually electromechanically controlled distributors are used, which establish a connection between pneumatic and electrical control. They switch via output signals from the control system and open or close the connection lines in the power part of the pneumatic actuator.

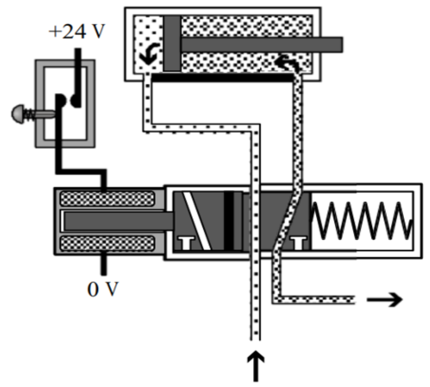
Purpose of electromagnetic actuators in distributors:
- Connecting or stopping the supply of compressed air.
- Extending and retracting cylinder drives.

The double-acting cylinder shown in Figure is operated by a five-way, two-position valve.

- When the solenoid is de-energized, the left chamber of the cylinder is vented from pressure, and the right chamber is filled with air — the rod retracts.

- When electrical current is supplied to the solenoid, the valve switches. The left chamber of the cylinder is filled with air, and the right chamber is vented from pressure — the rod extends.

- When the current is cut off from the coil, the valve switches back, and the rod retracts.



Cylinder control using a distributor

Basic knowledge

ELECTRIC DRIVE

Electric drive

There are various types of electric motors designed to perform different functions.

Electric motors can produce both rotational (rotary) and linear (reciprocating) movements.

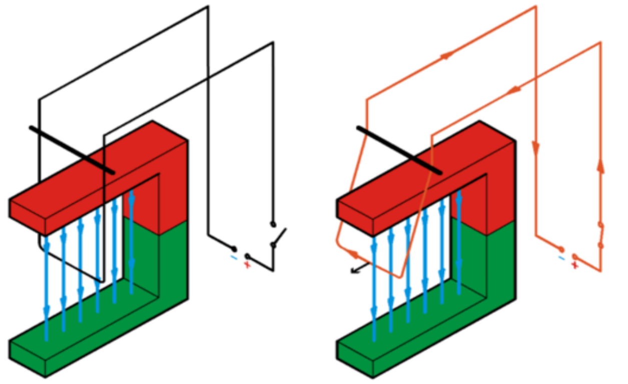
Physical/Technical Foundations of a DC Motor

If a wire carrying current I is placed in a magnetic field B, then a force F acts on that wire.

The direction of this force can be determined using the left-hand rule. Assume that the magnetic field lines go from the north pole to the south pole of the magnet, and that the current in the wire flows from the positive terminal of the power source to the negative terminal.

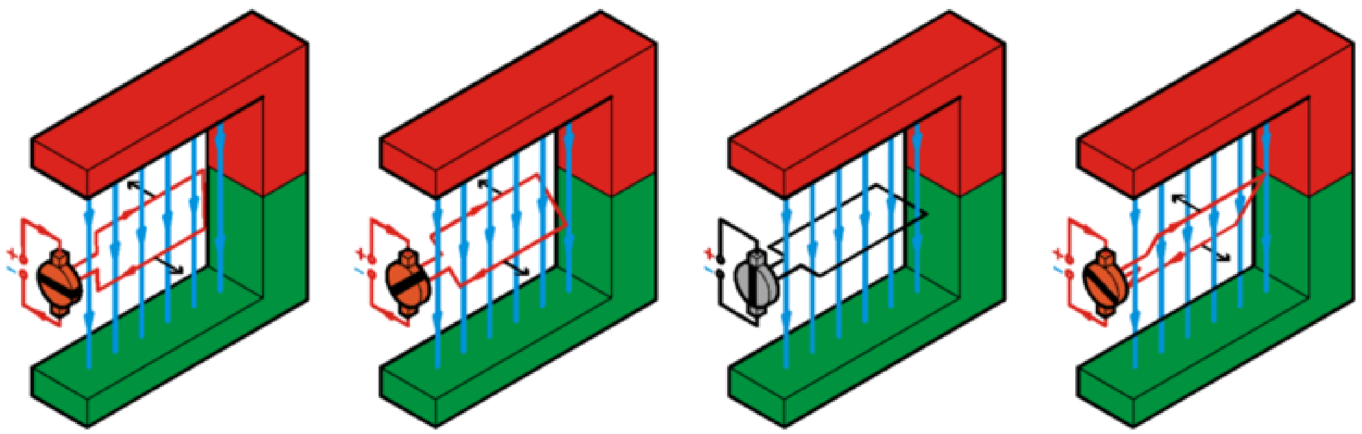
The three fingers (thumb, forefinger, and middle finger) are held perpendicular to each other to form a Cartesian coordinate system. When the thumb points in the direction of the current flow (from the positive to the negative terminal), and the forefinger points in the direction of the magnetic field (north/south), the middle finger indicates the direction of the force.

In the diagram, the wire will exit the plane of the magnetic field.



Lorentz force

The magnitude of the force depends on the strength of the magnetic field, the current, and the length of the wire located in the magnetic field.
In a direct current (DC) motor, this force is used to generate rotation. To achieve this, a conductive coil is placed between two magnetic poles so that it can rotate.



Principle of operation of a DC motor

Current flows through the two halves of the coil in opposite directions. This means that the direction of the force acting on them is also opposite. Their polarity is set so that they either attract (north/south or south/north) or repel (south/south or north/north) the poles of the permanent magnet. Both forces create a torque that causes the coil to rotate.

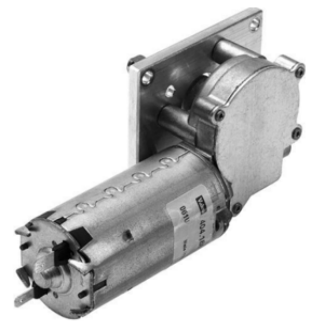
Basic knowledge

PROGRAMMABLE LOGIC CONTROLLERS

The mechanical commutator (current converter) switches the polarity of the current after half a turn of the coil, and the process repeats.
The commutator is an important component because it creates continuous rotation by reversing the force acting on the current-carrying conductor. It consists of two insulated metallic half-cylinders, on which current is transferred via carbon brushes.
Since a DC motor produces a low torque M_d at high speeds n, a gearbox is used as a transmission element to reduce the output speed n_2 by the gear ratio i and increase the output torque proportionally:

$$i = n_1/n_2 = Md_2/Md_1$$

Gearboxes come in various designs. In Figure, a DC motor with a worm gear reducer is shown, where the drive shaft is turned by 90° relative to the motor shaft.



DC motor with a gearbox

Programmable Logic Controllers

Any machine capable of automatically performing certain operations includes a controller (English: control unit) — a module that ensures the device's operational logic.

Technically, controllers are implemented in various ways. It could be a mechanical device, a pneumatic or hydraulic automatic, a relay or electronic circuit, or even a computer program. Controllers based on relays or integrated circuits with "fixed" logic cannot be easily reprogrammed to perform different tasks without significant modifications.

Obviously, only programmable logic controllers (PLCs) have such flexibility.

Programmable Logic Controller (PLC) is a microprocessor device designed for controlling technological processes in industry and other complex technological objects.

The principle of PLC operation involves collecting signals from sensors and processing them according to a user-defined application program, then outputting control signals to actuating devices.

A programmable controller is a digitally controlled discrete automatic device with a set of inputs connected via sensors to the control object and a set of outputs connected to actuators. The PLC monitors the states of inputs and produces specific sequences of programmed actions, reflected in changes at the outputs.

PLC is intended to operate in real-time conditions within an industrial environment and should be accessible for programming by non-specialists in information technology.

Main functions performed by PLC in control systems include management, protection, measurement of physical signals, display, and recording of technological processes. The PLC is a key functional element of modern automation control systems (ACS).

Principle of operation of a PLC

Basic knowledge
PLC CLASSIFICATION

PLC Classification

PLCs are a typical microprocessor-based system. Common devices such as the processor (CPU), non-volatile real-time clock, and memory (flash EPROM), RAM, controllers for connecting serial ports (RS-232), office (Ethernet), and industrial (field bus) networks are connected to the system bus. Additionally, various input and output signal devices are connected to the system bus.

A characteristic feature of PLCs is the ability to expand their configuration via the system bus, meaning that additional input/output devices can be directly connected to the bus.

Despite the variety of PLCs, they can be classified into the following groups:

1. Single-unit simple PLCs (intelligent relays).
2. Modular PLCs.
3. Specialized PLCs.

Moreover, these PLCs record data and send reports to SCADA systems of substations.

Standards for PLC Programming Languages (IEC 61131-3)

The processing of PLC input states into output states is carried out using a program. Therefore, before using a PLC, it needs to be programmed.

In 1979, an expert working group was established within the International Electrotechnical Commission (IEC) to address issues related to PLCs, including hardware, programming, installation, testing, documentation, and communication.

The first version of the IEC 61131 standard was published in 1982. Due to the complexity of the document, it was decided to split it into several parts.

Currently, the standard includes the following parts:

1. General information.
2. Equipment requirements and tests.
3. Programming languages.
4. User guides.
5. Message specifications.
6. Industrial networks.
7. Fuzzy logic programming.
8. Guidelines for application and implementation of PLC languages.

The third part (IEC 61131-3) is dedicated to PLC programming languages. According to it, five programming languages are considered standard:

- Three graphical:
  - Ladder Diagram (LD, LAD, RCS) — relay (ladder) logic language
  - Function Block Diagram (FBD) — functional logic block language
  - Sequential Function Chart (SFC) — sequential function diagram language
- Two textual:
  - Instruction List (IL) — low-level, processor-independent, assembly-like language
  - Structured Text (ST) — Pascal-like text programming language

All PLC manufacturers adhere to the IEC 61131-3 standard. A specialist trained in a program that includes the IEC 61131 standard will be able to work with PLCs from any company.

Basic knowledge
ELECTRIC DRIVE

1. TIA Portal (Totally Integrated Automation Portal) — An Integrated Development Environment

TIA Portal is an integrated development environment for automation system software, covering everything from drives and controllers to human-machine interfaces (HMI).

2. PLC Programming Language Ladder Diagram (LD)

Ladder Diagram (LD, LAD) is a relay (ladder) logic language designed for programming PLCs. Its syntax is convenient for replacing relay-based logic schemes. It is aimed at automation engineers working in industrial plants. It provides a visual interface for controller logic, simplifying programming, commissioning, and troubleshooting connected equipment.

3. Main Elements of LD Programming Language

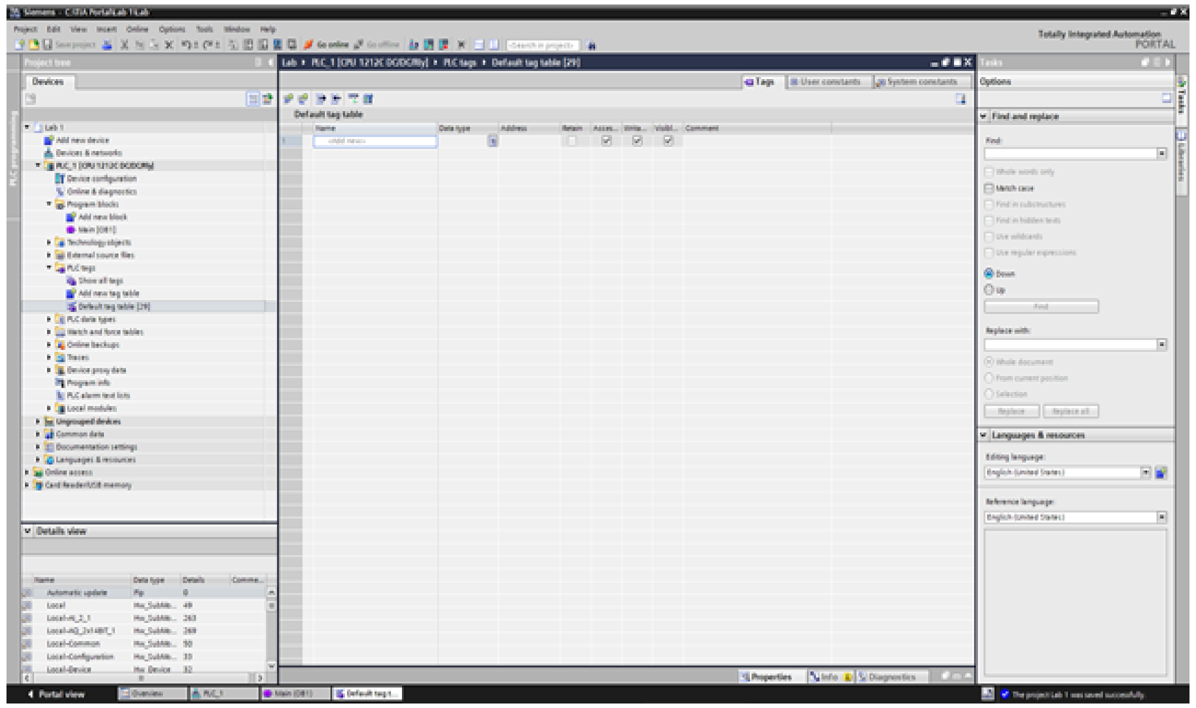
The basic elements are contacts, which can be metaphorically compared to relay contacts or buttons. Each pair of contacts is associated with a logical variable, and the state of the pair corresponds to the variable's value.

4. Special Logical Functions

When programming PLCs, it is often necessary to use specialized logical functions, such as:

- Counters
- Timers
- Pulse detectors
- Regulators
- Signal generators
- Analog comparators, etc.

These are ready-made functional blocks that simplify program writing and help solve various tasks during PLC programming.



Program window