# Automation and control of hydromechanical processes in industrial systems

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**Abstract:** *This report examines the basic principles, components and methods for the automation of hydromechanical processes used in modern industrial systems. The fundamental physical laws on which hydraulics is based are analyzed, as well as the role of sensors, actuators and control devices in the construction of closed automated control systems. Special attention is paid to security, diagnostics and the use of intelligent methods for monitoring and preventive maintenance. The presented solutions demonstrate the importance of automation in increasing the efficiency, reliability and safety of hydraulic systems. In addition, the report outlines current trends in the integration of hydraulic systems with programmable logic controllers and industrial communication networks, enabling adaptive control and real-time data exchange. Emphasis is also placed on energy optimization and the reduction of operational costs through advanced control strategies.*

**Keywords:** *industrial systems, maintenance, automation, sensors*

## 1. INTRODUCTION

The automation of hydromechanical processes occupies a key position in the development of modern industry, where high reliability, precision, and energy efficiency are required. Hydraulic systems are widely used in mechanical engineering, construction, transportation, and production lines due to their ability to transmit large forces within relatively compact dimensions. With the advancement of electronics, programmable logic controllers, and industrial communications, traditional hydraulic systems are evolving into intelligent automated complexes with self-diagnostic and adaptive control capabilities. The purpose of this report is to present the basic principles of hydraulics and to analyze the role of automation in the control, safety, and optimization of hydromechanical processes. An essential characteristic of modern automated hydraulic systems is the ability to precisely control the main operating parameters: pressure, flow rate, and the speed of actuators. This is achieved through the application of proportional and servo-controlled valves combined with sensors and feedback systems.

Thanks to the use of programmable logic controllers and digital regulators, high accuracy, repeatability, and process stability are ensured even under variable loads. Continuous monitoring of the system's condition allows for the timely detection of deviations and malfunctions, thereby increasing operational safety and reducing maintenance and repair costs. In addition to controllability and reliability, the automation of hydromechanical processes plays a crucial role in improving the energy efficiency of industrial systems. Through adaptive control and optimization of operating modes, a better match between supplied energy and actual technological demands is achieved. The integration of hydraulic systems with industrial communication networks creates conditions for centralized control, data analysis, and the implementation of predictive maintenance strategies. This contributes to reducing energy losses, extending the service life of equipment, and increasing the overall efficiency of production processes. Figure 1 shows the scheme of the multifaceted impact of automation in hydraulic systems.[3]

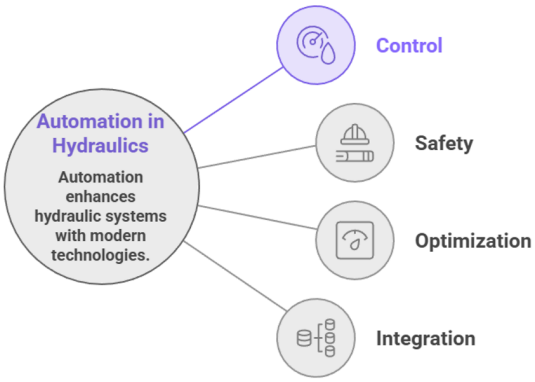



**Fig. 1.** Multifaceted Impact of Automation in Hydraulics

## 2. FUNDAMENTALS OF HYDRAULICS

Hydraulics is a technology that converts a small input effort into a very large force, based on the property of fluids to transmit pressure with minimal loss. In a historical context, from ancient times (ceramic and wooden rings used to regulate water flow) to modern composite materials and digital controllers, the principle of pressure transmission has remained the core of all systems requiring both force and precision. Today, hydraulics is indispensable in industrial machinery, construction equipment, automobiles, aircraft, and even laboratory installations, where precise manipulation of heavy loads with minimal effort is required. The foundation of hydraulics is Pascal's law: when pressure is applied to a confined, nearly incompressible fluid, it is transmitted uniformly in all directions. This means that the force acting on a cylinder with a given cross-sectional area is a direct function of the pressure. By increasing either, the area or the pressure, a greater force can be obtained without changing the fluid itself. However, pressure distribution alone is not sufficient. In order to create motion, flow must be controlled. Fluid flow follows the continuity principle: when the pipe cross-section is reduced, the flow velocity increases. In addition, pressure losses occur during flow in pipes, which are calculated using appropriate formulas. These losses are critical when designing systems with high pressure differentials and require proper selection of pipe diameter and material. The key components of a typical hydraulic system are the reservoir (stores the fluid), the pump (the unit that generates pressure), the valves (control direction and



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flow rate), and the actuators (cylinders that convert pressure into mechanical motion). For precise control and safety, sensors for pressure, temperature, and position are added; these measure system variables and transmit data to a PLC (Programmable Logic Controller). The PLC, following a program written in accordance with IEC 61131-3, regulates the valves and the pump to maintain the desired pressure and motion. Safety in hydraulic systems is ensured by pressure-relief valves, which open automatically when a preset threshold is exceeded, and by isolating valves that allow local shutdown of flow without interrupting the entire system. These devices also rely on Pascal's law: when pressure becomes excessive, the valve opens, redistributing energy and preventing damage.[5]

– **Physical Principles**

Hydraulics is based on two fundamental physical principles: Pascal's law and the law of conservation of energy. Pascal's law states that, at constant temperature and in a confined, nearly incompressible medium, pressure applied at one point is transmitted proportionally and simultaneously to all other points. This enables the conversion of energy into mechanical force through a simple calculation:

$$F = P \times A \tag{1}$$

where F is the applied force, P is the system pressure, and A is the cross-sectional area of the cylinder. This makes hydraulic systems highly energy-efficient - almost all mechanical work results from a small pressure difference acting over a large area. For the dynamic behavior of fluids, the continuity equation and Bernoulli's energy equation are used. For laminar flow through a pipe:

$$\rho v \times dV = 0 \;\Rightarrow\; v = \frac{Q}{A_{(tr)}} \tag{2}$$

where $Q$ is the volumetric flow rate and $A_{(tr)}$ is the cross-sectional area of the flow. Flow patterns involving pressure surges and pulsations are described by the Navier-Stokes equations, which are essential in pipeline design, where pressure loss is calculated as:

$$\Delta P = f \times \left(\frac{L}{D}\right) \times \frac{\rho v^2}{2} \tag{3}$$

Here, $P$ is the pressure loss, f is the friction factor, L is the pipe length, $D$ is the diameter, $\rho$ is the fluid density, and v is the flow velocity. This expression is fundamental for determining the required pump power and selecting pipe diameters in order to minimize energy consumption. Cross-flow in valves is described by the Darcy-Weisbach equation for throttling, while heated zones are modeled using heat-loss equations:

$$\Delta T = \frac{Q}{c_{(p)} \times m} \tag{4}$$

where $Q$ is the heat flow, $c_{(p)}$ is the specific heat capacity, and $m$ is the mass flow rate. Automatic temperature control using integrated thermistors (RTDs) is often required to prevent overheating and corrosion.

Cylinder force: $F_{cyl} = P_{act} \times A_{cyl}$
Pump pressure: $P_{pump} = P_{output} + \Delta P_{loss}$
Valve actuation force: $P_{valve} = k_{valve} \times Q_{flow}$

These equations make it possible to calculate the required cylinder cross-sectional area, the properties of the working fluid, and the necessary pipe diameter in order to achieve minimal pressure losses [6].

## 3. AUTOMATION COMPONENTS

In modern automated hydraulics, the key devices are divided into three main groups: sensors, actuators, and control elements. Their interconnections form a closed-loop feedback system, ensuring accuracy, stability, and operational safety.[7]

– **Sensors**

– Sensors in hydraulic systems measure pressure, temperature, flow rate, and position, converting physical quantities into electrical signals that are transmitted to the controller. This data enables precise monitoring and automatic control, ensuring safe and efficient operation of the entire system.

– Pressure transducers – operate with 0-10 V or 4-20 mA outputs, calibrated to ±0.5% of the full-scale pressure.

– Position sensors (LVDT / capacitive sensors) – measure position with a resolution of up to 0.01 mm, converting displacement into an analog signal.

– In-line flow meters (Coriolis, differential pressure types) – provide flow rate measurement with an error below 1 %.

– Temperature sensors (RTDs) – equipped with a protective shutdown signal when the temperature exceeds 80 °C. Figure 2 shows a position system sensor.[4]

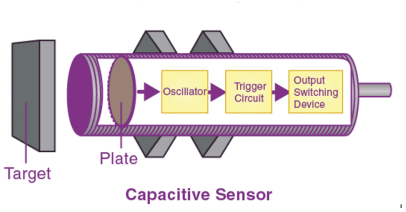



**Fig. 2.** Position sensor [9]

– **Actuators**

– **Electrohydraulic valves** - electrically actuated valves operating with 0-10 V control signals, with a response time of less than 10 ms.

– **Electropneumatic actuators** - combine electrical and pneumatic systems for lower power applications (≤ 5 kW) .

– **Hydraulic cylinders (reciprocating)** - typically manufactured from 304/316 stainless steel with reinforced sealing elements (O-rings, NBR).

– **Pump-servo units** - use electronic control of shaft speed to optimize hydraulic flow. Table 1 shows the most common actuators.

**Table 1.** Most Common Actuators.

| Type | Operating principle | Key parameters |
|---|---|---|
| Cylinder | Internal pressure – displacement of the plunger | Diameter, stroke length, speed, type |
| Rotary motor | Pressure – torque | Housing type (gear/-vane) – torque and rotational speed |
| Servo actuator | Precise valve control – accurate positioning | Sensitivity, control signal (4–20 $mA$ / 0–10 $V$) |

– **Control Devices**

Control devices such as PLCs and DCSs convert sensor signals into electrical outputs that regulate valves and pumps, ensuring precise and reliable hydraulic control. These systems typically include safety functions, remote monitoring capabilities via HMI/SCADA, and integration with industrial communication networks such as EtherNet/IP or Profinet. The most commonly used control systems in practice include:

– **Programmable Logic Controller** - CPU with I/O modules, programmed in accordance with IEC 61131-3 (Ladder Diagram, Structured Text).

– **Distributed Control System** - utilizes larger, centralized control stations, typically applied in large-scale machinery and industrial installations.

– **Network protocols** - Modbus TCP, OPC UA, EtherNet/IP, CAN FD, enabling high-speed data exchange (IEEE 2022).

– **Real-Time Operating Systems** - in PLC-based systems, RTOS ensures deterministic timing for safety-critical processes.[2]

Control devices also manage system safety (emergency outputs, alarms, fail-safe logic), energy balance (automatic pump regulation based on demand), and optimization (wear prediction models, for example through machine learning, integrated into SCADA or IoT gateways). Thus, from simple on-off control to advanced PID and feedforward control schemes, the control layer transforms sensor data into precise, reliable, and safe actuator actions, making the entire hydraulic process fully automated and controllable.

– **Safety and Diagnostics**

These mechanisms not only protect equipment but also enhance operational reliability: Pressure relief valves open automatically when pressure exceeds a preset threshold, preventing overheating and potential system failures or explosions. Isolation valves allow localized flow shutdown without interrupting the entire system, which is critical during maintenance and repair operations. Digital twins create virtual replicas of the system, continuously synchronizing data from real-time inputs and predicting potential issues, enabling preventive actions before failures occur. Together, these components form the essence of "smart" hydraulics systems capable of monitoring, diagnostics, and automatic adaptation to changing conditions while maintaining a high level of reliability and safety.



## 4. APPLICATIONS OF AUTOMATED HYDRAULIC SYSTEMS

Automated hydraulic systems are widely used in industry due to their ability to deliver high forces, smooth control, and high reliability. They are applied in environments where mechanical or purely electrical drives are insufficient in terms of power or durability. The combination of hydraulics and automation enables the execution of complex technological processes with high precision and repeatability. In mechanical engineering, automated hydraulic systems are a core element in the operation of presses, lathes, milling machines, and forming equipment. Figure 3 shows the versatility of the applications of automated hydraulic system.

Although public discourse around generative artificial intelligence is dominated by software breakthroughs and abstract algorithmic capabilities, its practical realization is inextricably tied to the material infrastructure of modern computing systems. Every advance in models is a function of real physical resources - semiconductors, energy, cooling, and network connectivity. This dependence places a ceiling on the economic scalability of AI and gives rise to the so-called "hardware wall" - the point at which additional investment in computational power yields diminishing returns and increasing systemic risk.[3]

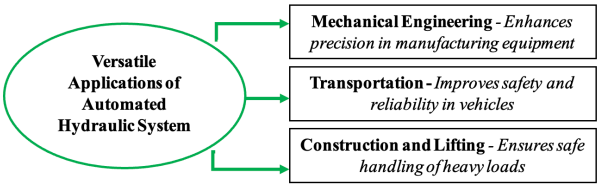



**Fig. 3.** Versatile Applications of Automated Hydraulic System

Through the use of PLC-based control and sensor feedback, precise positioning, force control, and motion synchronization are achieved. This leads to improved product quality and a reduction in production defects. In construction and lifting equipment, hydraulics is practically indispensable. Machines such as excavators, mobile cranes, lifts, and hydraulic platforms rely on automated hydraulic drives for the safe handling of heavy loads. Integrated monitoring systems enable load control, stability supervision, and the prevention of emergency situations. Automated hydraulic systems are also widely used in the transportation sector, including aviation, rail, and automotive industries. Typical examples include hydraulic braking systems, steering mechanisms, and aircraft landing gear control systems.

## 5. ENERGY EFFICIENCY AND OPTIMIZATION

Energy efficiency is one of the key factors in the design and operation of modern automated hydraulic systems. Due to high operating pressures and continuous duty cycles, inefficient systems can lead to significant energy losses and increased operating costs. Therefore, optimization of the energy balance is a critical task. One of the primary methods for improving efficiency is the use of variable-displacement pumps and frequency-controlled electric motors. Instead of operating continuously at maximum flow, the system adapts its output to the current load demand. This significantly reduces unnecessary energy consumption and heat generation. An additional optimization approach involves minimizing hydraulic losses through proper selection of pipe diameters, high-quality valves, and suitable working fluids. Reducing friction and turbulence losses leads to higher overall efficiency and extends the service life of system components. Modern automated systems also employ intelligent control algorithms, such as PID and adaptive controllers, which optimize operation in real time. Integration with SCADA and IoT platforms enables data analysis and the identification of inefficiencies. Table 2 and figure 4 shows the key energy efficiency indicators of a hydraulic system.[1]

**Table 2.** Key Energy Efficiency Indicators of a Hydraulic System.

| Indicator | Conventional System | Optimized System |
|---|---|---|
| Average Power Consumption $[kW]$ | 38 | 24 |
| Annual Energy Consumption $[MWh]$ | 304 | 192 |
| Overall Energy Efficiency [%] | 70 | 88 |
| Hydraulic Oil Temperature $[^{\circ}C]$ | 68 | 52 |
| Annual Operating Costs [EUR] | 36,500 | 23,000 |

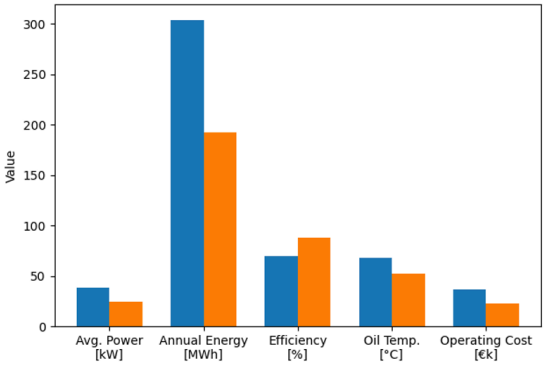



**Fig. 4.** Comparison of Energy Efficiency Indicators between Conventional and Optimized Hydraulic Systems

## 6. ADVANTAGES AND LIMITATIONS OF AUTOMATED HYDRAULICS

One of the main advantages of automated hydraulic systems is their ability to generate very large forces with compact actuator dimensions. This makes them particularly suitable for applications requiring high power and precision. In addition, hydraulics allows smooth and continuous regulation of speed and force. Automation further enhances the reliability and accuracy of these systems. Through the use of sensors and closed-loop control circuits, con-

stant monitoring of pressure, position, and temperature is ensured. This reduces human intervention and minimizes the risk of operational errors. Despite their many advantages, automated hydraulic systems also have certain limitations. The main disadvantages are related to system complexity, higher initial investment costs, and the need for qualified maintenance personnel. Leakage of hydraulic fluid can lead to efficiency losses and environmental concerns. Another limitation is the sensitivity of hydraulic systems to contamination and temperature variations. This necessitates the use of filters, cooling systems, and regular preventive maintenance. Nevertheless, with proper design and operation, automated hydraulics remains one of the most effective solutions for industrial applications.[8]

Table 3 summarizes the key advantages and limitations of automated hydraulic systems. While their high-power density and precise controllability make them ideal for demanding industrial applications, challenges related to system complexity, maintenance requirements, and environmental considerations must be addressed through proper design and operation.

**Table 3.** Advantages and Limitations of Automated Hydraulic Systems.

| Aspect | Advantages | Limitations |
|---|---|---|
| Force-to-size ratio | Very high output forces with compact actuator dimensions | High pressures require robust and expensive components |
| Control and precision | Smooth, continuous control of speed and force; high positioning accuracy | Sensitive to contamination affecting control accuracy |
| Automation and monitoring | Sensors and closed-loop control enable real-time monitoring of pressure, position, and temperature | Increased system complexity due to additional sensors and control hardware |
| Reliability and safety | Reduced human intervention and minimized operational errors | Requires qualified maintenance personnel |
| Operating conditions | Suitable for heavy-duty and high-power industrial applications | Sensitive to temperature variations and hydraulic fluid leakage |

## 7. CONCLUSIONS

The automation of hydromechanical processes represents a key factor in the development of modern industrial systems. By integrating hydraulic drives with sensors, controllers, and intelligent software, high efficiency, precision, and operational safety are achieved. This report examined the fundamental physical principles of hydraulics, as well as the main components of automated systems—sensors, actuators, and control devices. Safety and diagnostic mechanisms were also analyzed, as they play a decisive role in ensuring reliable system operation. Particular attention was given to energy efficiency and optimization possibilities, which are essential under conditions of rising energy costs. Modern technologies enable intelligent control and predictive maintenance, significantly extending the operational lifetime of equipment. In conclusion, automated hydraulic systems will continue to evolve toward greater intelligence, deeper integration with Industry 4.0 concepts, and the use of artificial intelligence. This makes them a strategically important element in future industrial and technological solutions.



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