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Comparison of hydraulic, pneumatic and electric actuators

Interdisciplinary project

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1 Introduction

Actuators are essential components in modern engineering and automation, serving as critical elements in various mechanical and industrial systems. They convert energy into mechanical motion, enabling precise control over movement in numerous applications, from robotics and manufacturing to aerospace and healthcare. The selection of an appropriate actuator type is crucial in optimizing performance, efficiency, and reliability within a given system. Among the most widely used actuators are hydraulic, pneumatic, and electric actuators, each utilizing different energy sources to generate motion. Hydraulic actuators rely on pressurized fluid to produce force, making them ideal for applications requiring high power and heavy loads. Pneumatic actuators operate using compressed air, offering rapid motion and lightweight operation, commonly found in automation and assembly lines. Electric actuators, driven by electric motors, provide high precision, efficiency, and control, making them suitable for robotics and other automated systems requiring accuracy.

Understanding the differences between these actuator types is essential for engineers and designers when selecting the most appropriate option for specific applications. Each actuator type has distinct advantages and limitations regarding force output, speed, control precision, efficiency, maintenance, and environmental impact. The choice between hydraulic, pneumatic, and electric actuators depends on various factors, including the nature of the task, operating environment, and cost considerations.

This thesis presents a detailed comparison of hydraulic, pneumatic, and electric actuators, focusing on their working principles, advantages, disadvantages, environmental impact, and applications. A significant emphasis will be placed on evaluating their force output, speed, control precision, energy efficiency, maintenance requirements, and overall suitability for various industrial applications.

2 Overview of actuators

Like mentioned before actuators are essential in modern mechatronic systems, enabling precise control in applications such as robotic manipulators, industrial valves, and prosthetic limbs. The primary function of an actuator is to execute a specific movement-linear, rotary, or oscillatory-based on input signals from a control system. The choice of actuator depends on factors such as required force, speed, precision, energy efficiency, and environmental conditions.[3]

Actuators can be classified based on their energy source into three primary categories: hydraulic, pneumatic, and electric actuators. Each of these types operates using distinct mechanisms and is suited for specific applications depending on factors such as force output, speed, efficiency, and control precision.

Hydraulic actuators utilize pressurized fluid (typically oil) to generate motion. They are known for their high force output and robustness, making them ideal for heavy-duty applications. Hydraulic systems are widely used in construction machinery, aerospace controls, and industrial presses due to their ability to handle extreme loads. However, they require complex maintenance due to potential fluid leaks and energy inefficiencies.

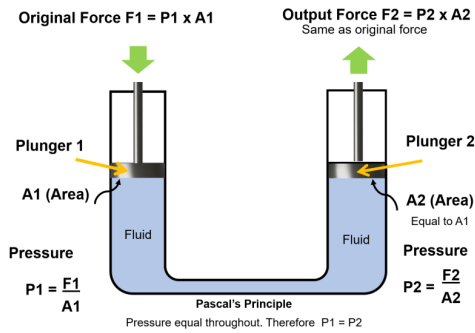
Pneumatic actuators operate using compressed air or gas to produce motion. They are favored for their simplicity, rapid response, and cost-effectiveness [2]. However, their precision is limited by air compressibility, and they generate noise during operation.

Electric actuators employ electric motors (such as servo, stepper, or DC motors) to convert electrical energy into mechanical motion. They are highly precise, programmable, and energy-efficient, making them suitable for applications requiring fine control. However, they may struggle with high-force applications and can overheat under continuous use [4].

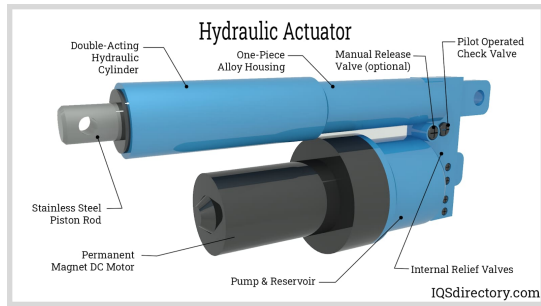
3 Hydraulic actuators

3.1 Working principle

Hydraulic actuators function based on Pascal's principle, which states that pressure applied to an incompressible fluid (typically hydraulic oil) is transmitted equally in all directions. A hydraulic pump pressurizes the fluid, which then flows through control valves into a hydraulic cylinder or motor. The pressurized fluid acts on a piston or rotary vane, converting fluid energy into linear or rotary mechanical motion [2]. These systems are highly efficient in force transmission, allowing for smooth and controlled movement even under extreme loads. The ability to generate substantial force with relatively small components makes hydraulic actuators indispensable in heavy machinery and high-power applications [3].



(a) Pascal's principle



(b) Example of Hydraulic actuator

3.2 Components

A hydraulic actuator system will typically consist of the following fundamental components that are required for it to operate:

The central and essential component of the entire system, which is commonly known as the hydraulic pump, plays a very crucial role in maintaining and developing the necessary pressure in the hydraulic fluid. Some of the most common ones are vane pumps, gear pumps, and piston pumps. Fluid pressure undergoes a transformation to mechanical motion, made achievable by the utilization of hydraulic motors and cylinders that have specifically been designed for the transformation. Hydraulic motors, for instance, play a crucial role in the operation of rotary actuators, enabling them to operate optimally, while hydraulic cylinders are key components that are utilized by linear actuators to achieve their intended motion. Control valves regulate the flow rate, pressure, and flow direction of hydraulic fluid. Flow control valves, pressure relief valves, and directional control valves are some examples. A reservoir, or fluid tank, plays the important role of preventing contamination as well as effectively dissipating heat by holding hydraulic fluid throughout the process. The hydraulic fluid is readily transferred from one component to the next through hydraulic hoses and fitting suitably designed for the task, thereby maintaining pressure integrity within the system.

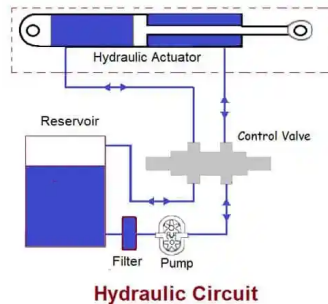


Figure 2: Hydraulic actuator system

3.3 Advantages and disadvantages of hydraulic actuators

Hydraulic actuators control equipment motion and power. Although handy for applications with high power, their design needs to counter disadvantages. Hydraulic actuators are superior to other approaches in achieving high torque and force. Although other methods can generate favorable forces in small sizes, hydraulics do their job better in the big sizes. Their power density is high based on fluids being incompressible and thus allowing power to be transmitted with less loss. Hydraulic systems are capable of developing much greater forces than similar sized electric actuators and are suitable for construction equipment such as cranes and excavators to lift heavy loads precisely [1]. The appropriateness of hydraulic actuators for heavy-duty use is yet another enormous benefit that cannot be ignored. These cutting-edge systems actually perform better than others in stressful conditions that demand long-term high-force usage, like those seen in industrial presses or in most types of mining machines. The solid and durable construction of these systems enables them to resist and endure a wide range of severe operating conditions, not only exposure to dust but also water and extreme temperature variations that would otherwise degrade the performance of other actuation technologies. Well-maintained and properly serviced hydraulic systems have been proven by research studies to be capable of running reliably and efficiently for decades even under exposure to the severe and rigorous conditions that are common in most industrial settings [2]. This high strength is one main driving force behind their wide use in most markets where equipment failures equate to enormous downtime costs in addition to monetary loss. High precision control is another worthwhile third main benefit for hydraulic actuation that pertains to their capability for more than just strength. Far from most people's realization, hydraulic systems today can not only deliver very smooth but also high precision motion control. Such high precision is achievable by utilizing sophisticated valve technologies in combination with very advanced closed-loop control systems that, in combination, achieve very accurate positioning to sub-micrometer scales in some specialty application systems.

Precisely designed hydraulic actuators are best suited to high-control applications such as injection molding and airplane surfaces. Their even force response supports reliability in precision applications [3].

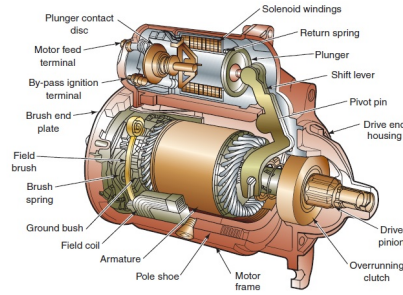
One of the major disadvantages of hydraulic actuators is their complicated maintenance. Maintenance is required regularly to avoid fluid leakage. Hydraulic fluid can damage precision parts, as seen in 75% of hydraulic system failures in 2022 caused by PMC contamination. This maintenance increases cost and downtime in comparison to other actuation technologies. Energy is wasted in hydraulic systems. Pumps are always on and are only 40% to 60% efficient compared to electric systems [2]. Inefficiencies in periodic duty cylinders waste energy during idling. Variable displacement pumps and accumulators do enhance efficiency to some extent, but some thermal limits are unchanged.

The hydraulic systems are heavier and more complex compared to electric or pneumatic ones because of pumps, hoses, valves, and reservoirs. Weight is significant in mobile equipment since it affects payload and fuel efficiency [1]. Hydraulic line requirements complicate routing and introduce points of failure. Environmental conditions are also important in hydraulic system analysis. Leaking fluids are of primary concern due to their risk of causing harm to the environment and safety risks in ecologically sensitive areas. Traditional hydraulic fluids have the potential to contaminate soil and water, causing regulatory difficulties and elevating the call for biodegradable alternatives [4]. Noise from hydraulic pumps and thermal management requirements create problems in noise-constrained or thermal-constrained applications. Hydraulic actuators are best suited to applications with high forces that require them to be valued for their robustness, high precision control, and functionality in a variety of industrial or mobile applications. [3].

3.4 Key application of hydraulic actuators

Hydraulic actuators play crucial functions in numerous sectors due to their high power density and reliability in unfavorable settings. Hydraulic systems power excavators, cranes, and bulldozers, providing the massive force needed for digging and lifting operations in response to tough working conditions at construction sites. Hydraulic actuators in aircraft's flight control systems and landing gear handle large loads and provide the accuracy to execute safe landings, takeoffs, and in-flight maneuvers. Hydraulic presses and injection molding machines apply hydraulic force to

allow metal shaping and plastic molding processes that require the capability to withstand high pressure and accuracy. Ship steering systems, stabilizers, and cargo equipment utilize hydraulic actuators for reliable operation in corrosive marine environments. Critical for oil/gas drilling safety systems and renewable energy applications like wind turbine pitch control. While being phased out in passenger vehicles, heavy trucks and agricultural machinery still depend on hydraulic steering and braking systems. Modern advancements like electro-hydraulic hybrids and smart sensors are expanding hydraulic applications into robotics and precision automation while addressing traditional efficiency limitations. These innovations ensure hydraulic actuators remain indispensable for high-force applications despite growing electrification trends.



(a) Hydraulic actuator



(b) Hydraulic actuator - cylinder in heavy machinery

Figure 3: Applications of Hydraulic actuators

4 Pneumatic actuators

4.1 Working principle

Pneumatic actuators are devices that convert the energy of compressed air into mechanical motion, facilitating the control of various mechanisms such as valves, dampers, and other industrial equipment. Their operation is based on the principles of pneumatics, where compressed air is utilized to produce linear or rotary movement. This document provides an in-depth exploration of the working principles of pneumatic actuators, their components, types, and operational dynamics.

There are several steps that can be used to understand how a pneumatic actuator works. First, the electrical and control systems regulate the compressed air flow to operate the actuator. The process is started by introducing compressed air through a control valve into the actuator's cylinder. A piston or diaphragm inside the actuator is affected by the compressed air once it enters the cylinder. The piston moves as a result of this compressed air. Whereas the piston in a rotary actuator generates rotational movement, the piston in a linear actuator produces straight-line motion. The linked load or mechanism then receives the mechanical output produced by the piston's movement. The actuator can accomplish the intended task, like opening or closing a valve, thanks to this motion. After completing its task, the actuator must prepare for the next cycle. To do this, the compressed air is vented out of the cylinder through exhaust ports, allowing the piston to return to its original position. This sequence of actions enables the pneumatic actuator to operate efficiently and repeatedly.

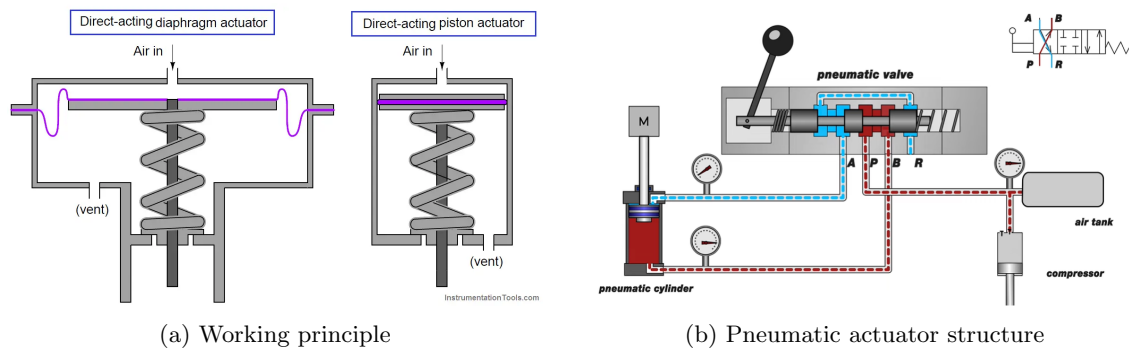


Figure 4: Working principle of Pneumatic actuators

4.2 Types of pneumatic actuators

4.2.1 Linear pneumatic actuators

Linear pneumatic actuators - also referred to as pneumatic cylinders are the most common type of pneumatic actuators. Their function is to produce a linear motion in response to the pressure of compressed air acting on a piston inside a cylindrical chamber. These actuators are fundamental components in factory automation, material handling, clamping systems, and pick-and-place machinery.

A typical linear actuator consists of a cylinder (tube), a piston, piston rod, end caps, seals, and one or more air ports. When compressed air enters the chamber on one side of the piston, it generates force that pushes the piston forward or backward. This movement is transmitted via the piston rod to perform mechanical task such as lifting, pressing, or moving an object.

There are two common configurations:

In single acting configuration, compressed air is applied to only one side of the piston. The return stroke is accomplished by a spring or by the load itself. Single-acting cylinders are energy-efficient for tasks that only require force in one direction. The second one is double-acting cylinders. In double-acting systems, air is alternately applied to both sides of the piston, enabling powered motion in both directions. This allows for higher control, precision, and repeatability, especially in

dynamic or cyclic operations.

Linear pneumatic actuators are used in conveying systems for pushing or ejecting objects. Packaging equipment to form, seal, or cut materials. Machine tools for clamping, drilling, or pressing operations. Automation tasks where compact and cost-effective motion is required.

4.2.2 Rotary pneumatic actuators

Unlike linear actuators, rotary pneumatic actuators produce rotational motion. These are essential in applications where parts need to be rotated, turned, or positioned with a defined angular displacement. Rotary actuators convert the linear force of air pressure into a rotational torque, often within a limited angular range (typically 90°, 180°, or 270°). Construction and Operating Mechanisms: Rotary actuators typically come in several designs, each utilizing different mechanisms to achieve rotation. Vane-type rotary actuators use one or two vanes attached to a central shaft inside a cylindrical chamber. When compressed air is introduced, the vane rotates about the shaft due to the pressure differential. They are compact and well-suited for quick and simple rotary actions.

While in rack and pinion rotary actuators, linear motion of a piston (or two pistons) is transferred to a rotary motion via a gear mechanism. The rack is connected to the piston, and it engages with a pinion that turns as the piston moves. This type offers higher torque and is more rugged for demanding industrial tasks. The helical (or Scotch yoke) rotary actuators use a helical slot or a yoke system to convert linear motion to rotation. They provide smooth torque output and are often used in valve actuation.

Rotary pneumatic actuators are used in industrial automation systems for part rotation, indexing, or flipping operations. Valve automation in fluid control systems (e.g., opening and closing of butterfly or ball valves). Robotics and material handling where rotational motion is essential. Packaging and bottling machinery for orientation and alignment of products.

4.3 Components

A pneumatic actuator system relies on several fundamental components working in concert to efficiently convert compressed air energy into controlled mechanical motion, as mentioned before. At the heart of the system lies the air compressor, the crucial power source that pressurizes atmospheric air to typical operating pressures between 4-8 bar. Common compressor types include reciprocating piston, rotary screw, and centrifugal designs, each selected based on required airflow rates and duty cycles.

The transformation from air pressure to mechanical movement occurs through precisely engineered pneumatic actuators, which come in two primary configurations. Linear actuators (pneumatic cylinders) utilize pressurized air acting on piston surfaces to produce straight-line motion, while rotary actuators employ vane or gear mechanisms to generate angular displacement, typically ranging from 90° to 270° of rotation, as explained before.

Directional control valves serve as the nervous system of pneumatic circuits, managing airflow paths with rapid response times often under 10 milliseconds. Common configurations include 3/2-way valves for single-acting cylinders and 5/2-way valves for double-acting applications, with solenoid or pneumatic pilot operation enabling automated control. Flow control valves provide precise adjustment of actuator speed by regulating air exhaust rates, while quick exhaust valves can significantly improve cycle times by creating optimized air discharge paths.

An essential supporting component is the air preparation unit (FRL - Filter, Regulator, Lubricator), which conditions the compressed air before it reaches sensitive components. Multi-stage particulate filters remove contaminants down to 5 micron levels, pressure regulators maintain consistent operating pressures within ± 0.2 bar, and micro-fog lubricators inject precisely metered oil droplets to reduce friction in moving parts.

The compressed air reservoir (receiver tank) plays multiple critical roles such as dampening pressure fluctuations from compressor cycling, providing surge capacity for peak demand periods, and allowing moisture to condense out of the air stream. Sizing follows industry standards based on compressor output and system air consumption rates.

Interconnecting all components, pneumatic tubing and fittings form the distribution network, with

materials ranging from nylon for general purposes to stainless steel for high-pressure or corrosive environments. Proper sizing ensures adequate flow capacity while minimizing pressure drops, with push-to-connect fittings enabling rapid assembly and maintenance. Modern systems increasingly incorporate electronic position sensors such as reed switches or Hall-effect devices for real-time feedback, while advanced configurations may include proportional pressure regulators for force control or networked valve manifolds for centralized automation. The complete system represents a carefully balanced combination of mechanical and pneumatic elements designed for reliable, high-speed operation across millions of cycles in industrial environments.

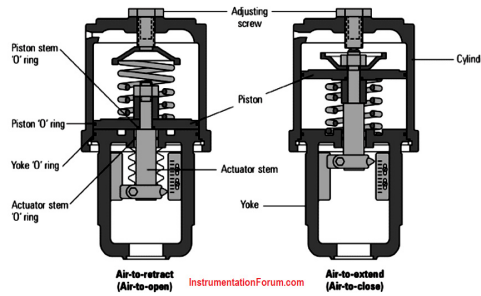


Figure 5: Main components of Pneumatic actuator

4.4 Advantages and disadvantages of pneumatic actuators

Pneumatic actuators are a vital component in modern industrial and automation systems, offering unique benefits that stem from their reliance on compressed air as a working medium. One of the most prominent advantages of pneumatic actuators is their clean operation, which makes them particularly suitable for environments that demand strict hygiene and minimal environmental impact, such as the pharmaceutical, food processing, and medical industries. Since air is non-toxic and abundantly available, pneumatic systems do not introduce harmful substances into the environment, unlike hydraulic systems that risk leakage of oil-based fluids. Moreover, pneumatic actuators offer fast response times and are capable of high-speed operation, attributes that make them ideal for rapid cycling applications, such as in automated packaging or assembly lines. Their design is typically simple and robust, with fewer moving parts compared to electric actuators, resulting in higher reliability, lower maintenance needs, and reduced downtime. In addition, pneumatic actuators are inherently safe for use in explosive or flammable environments, as they do not involve electrical currents or flammable fluids, further enhancing their versatility in industrial applications. However, despite these advantages, pneumatic actuators also come with several notable limitations that must be considered when selecting them for specific applications. One major disadvantage is their lower force output compared to hydraulic actuators. Because air is compressible, it lacks the density and power transmission capability of hydraulic oil, which makes pneumatic actuators less suitable for tasks that require very high force or torque, such as in heavy construction machinery or large-scale pressing operations. The compressibility of air also leads to a key performance drawback: reduced precision and control. Unlike electric or hydraulic actuators, pneumatic systems may exhibit inconsistent behavior under varying loads or pressure fluctuations, which can compromise accuracy in positioning-sensitive operations. Another practical concern is that pneumatic actuators require a continuous and well-regulated supply of compressed air, typically provided by compressors and extensive piping systems. This dependency can lead to higher operational costs over time, especially in facilities where air losses, leaks, or pressure drops are not adequately managed. Additionally, the efficiency of pneumatic systems is often lower due to energy losses associated with compressing and transporting air.

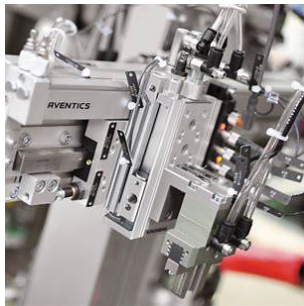
4.5 Key applications of pneumatic actuators

Key applications span fields where lightweight, cost-effective, and fast linear or rotary motion is needed, particularly in automation and control systems. One of the most significant areas of appli-

cation is industrial automation, especially in manufacturing and assembly lines, where pneumatic actuators are responsible for performing repetitive tasks such as pushing, pulling, lifting, clamping, or sorting components. These actuators are ideal for such tasks because they can operate quickly and reliably under controlled conditions, ensuring continuous production without frequent maintenance. In packaging industries, for instance, pneumatic actuators are used to control the opening and closing of flaps, driving conveyor systems, or pushing products into containers, where speed and synchronization are critical to maintain production throughput.

Another key domain is the automotive industry, where pneumatic actuators are employed in robotic arms and handling systems for welding, painting, or assembling parts. Their lightweight nature allows for flexible integration into robotic systems without adding excessive weight or requiring complex control mechanisms. Additionally, they are used in vehicle braking and suspension systems, particularly in heavy-duty trucks and buses, where air-actuated systems provide responsive and robust control. In the medical and pharmaceutical sectors, pneumatic actuators are essential due to their clean operation. They are found in laboratory automation equipment, such as pipetting systems and sample handling devices, where contamination-free environments are mandatory. The absence of oil or electrical sparks makes pneumatic systems ideal for cleanroom applications, where sterility is critical.

Pneumatic actuators also find applications in food and beverage processing, where hygiene regulations prohibit the use of lubricated or electrically active devices that might contaminate consumables. These actuators are used in bottling, filling, sorting, and packaging processes, ensuring fast and sanitary operation. In agriculture, pneumatic systems are employed in tasks such as controlling ventilation in greenhouses, automating feeding systems, or even actuating parts of agricultural robots. Furthermore, the growing field of soft robotics has begun to leverage pneumatic actuators soft, elastomer based versions for applications requiring delicate interaction, such as robotic grippers that can handle fragile produce or interact safely with humans. Expanding role of pneumatic actuators in biomedical devices and assistive technologies, where low force and soft motion are essential for safety and comfort [1] [5].



(a) Industrial automation



(b) Soft robotics

Figure 6: Applications of Pneumatic actuators

5 Electric actuators

5.1 Working principle

Electric actuators are necessary in today's automation and control systems to convert electrical energy into physical motion for an endless number of tasks across different industries. Electric actuators work based on the principles that govern electromechanics, which provide for a controlled linear or rotary motion. An electric motor, usually a servo, stepper, or traditional AC/DC motor, is a major component of an electric actuator that produces a rotary motion from electrical energy. That rotary motion can be transformed into linear motion using a mechanical assembly, normally a lead screw, ball screw, or belt driven assembly. The rotating motor case causes the screw assembly to drive the actuator rod or travel in and out or extend or retract the actuator, thus producing linear motion. The rotary motion of the motor's direction or speed defines the linear motion; the electronic integration provides more precision, allowing the linear motion to be controlled with high precision and re-accomplished much like a positioning task. Electric actuators are typically referred for their accuracy, efficient use of power, and flexibility in applications. They can be easily integrated into systems controlled by a computer for research or simply to automate various processes in manufacturing, robotics, and medical devices. They are clean when performing these tasks because the systems usually do not need hydraulic fluids or compressed air, which is especially important when contamination of surfaces needs to be controlled.

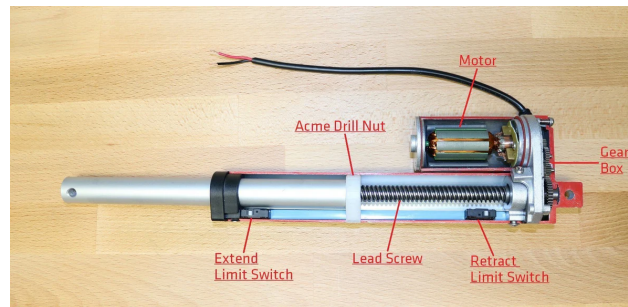


Figure 7: Example of a basic electric linear actuator

5.2 Types of electric actuators

Electric actuators have become essential elements of modern automation systems, as they deliver accurate control and efficient energy transformation in a wide range of industrial applications. Electric actuators are devices that change electrical energy into mechanical motion and operate under various electromechanical principles. Each electric actuator has its own unique qualities making it well suited to certain operational needs. This essay covers the main types of electric actuators, their means of operation, and their advantages in industrial applications.

5.2.1 Linear electric actuators

Linear electric actuators are one of the most widely utilized automation devices in industry. These units convert rotary movement from an electric motor into linear movement through transmission units. The most common designs employ a brushless AC or DC servo motor with a precision lead screw or ball screw. When the motor rotates, the screw mechanism translates rotary movement into linear actuator rod movement, up to positioning precision of ± 0.01 mm for high-performance applications. All linear actuators of today are recirculating ball bearings for reducing the friction and backlash, with more than 90% efficiency. These actuators are especially suited for valve control, medical equipment, and rapid-rate assembly systems that are requiring straight-line movement with repetitive motion. New tubular linear motor design have developed with major improvements towards preventing all modes of mechanical transmission for maintenance-free operation with extremely dynamic response.

5.2.2 Rotary electric actuators

Rotary electric actuators achieve angular movement through either gear reduction schemes that are direct or driving schemes that are motor driven. The workhorses of motors that are named servo motors serve the purpose of catering operations of high performance with continuous torque ratings between 0.1 Nm and 500 Nm with position resolution of under 0.01° . The actuators of such a type employ advanced feedback mechanisms that typically employ absolute encoders with a resolution of 20 bits and higher for angular position feedback. Industrial robotic operations employ harmonic drive actuators that have gained widespread acceptance because of their compact sizes and zero-backlash operation, and thus they are among the top contenders for application on articulated-arm joints. Stepper motor-powered rotary actuators are also available in the form of a low-cost variant for open-loop control position operation such as printer head position of 3D printer or telescope mounts. Limited-angle "torque" motors have also emerged as a specialty category that offers extremely high torque density for partial rotation operations such as aircraft control surface actuation.

5.2.3 Piezoelectric actuators

Piezoelectric actuators function based on different principles than electromagnetic devices, using ceramic materials such as PZT (lead zirconate titanate) to operate using the inverse piezoelectric effect. These materials experience changes in dimensions on the nanometer scale when placed under high voltage (typically 100 to 1000 V). When arranged into stacks, the straining mechanism is amplified to allow for practical levels of movement, but remain capable of sub-nanometer positioning. The actuators are especially suitable for applications dependent on extreme precision, such as in atomic force microscopy and optical alignment systems. The frequency response of piezoelectric actuators is capable of operating into the kHz range while also cancelling vibrations in precision machining equipment. Developments in multilayer piezo technology have allowed for reduced operating voltages while also further improving displacements allowing for further applications in adaptive optics and micropositioning systems.

Electric actuator selection depends on specific application needs such as precision, force, speed, and environment. Although electromagnetic actuators reign among automation applications due to their reliability and maturity, newer actuators like piezoelectric and electroactive polymer actuators keep pushing the frontiers of motion control in specialized applications. Recent improvements in material science and power electronics in the near future are bound to make such critical elements more efficient and cheaper, further tightening their grip on precision motion applications.

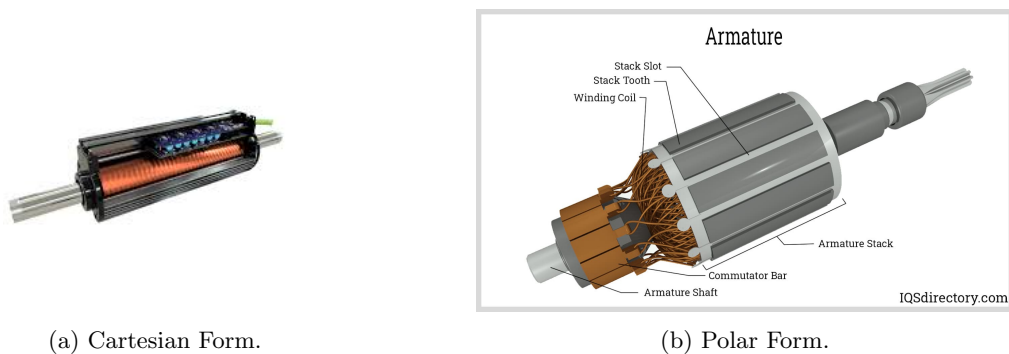


Figure 8: Electric actuators

5.3 Advantages and disadvantages of electric actuators

One of the key advantages of electric actuators is their clean operation and energy saving. In contrast, with hydraulic systems relying on oil-based fluids or pneumatic systems requiring a continuous supply of compressed air for operation, electric actuators function only on the application of electrical energy. This not only gives them an edge in terms of environmental considerations, but it also makes operating electric actuators in cleanroom-type environments such as hospitals, laboratories, and food processing plants more convenient. Electric actuators also require minimal maintenance due to their quite simple mechanical design with no fluid components, thereby minimizing the risks of leakage, contamination, or component wear due to pressure-based systems. They are compact and operate quietly, which is again an advantage in indoor or sensitive spaces where noise and space constrictions could be an issue.

However, electric actuators are not without their limitations. One significant drawback is their limited force output compared to hydraulic systems. While electric actuators can achieve high precision and moderate force, they are generally not suitable for applications requiring extremely high power, such as lifting heavy machinery or driving large industrial presses. Additionally, electric actuators may face challenges in hazardous or flammable environments, where sparks from electrical components could pose safety risks—areas where pneumatic actuators typically excel due to their non-electrical nature. Another consideration is that electric actuators are prone to overheating under continuous or high-load conditions, which may necessitate the addition of cooling systems or duty cycle management to maintain performance and longevity.

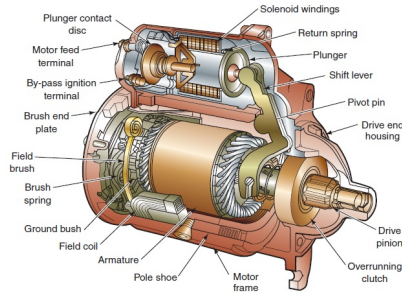
Despite these limitations, the continual advancement of motor technology, sensor integration, and digital control has significantly expanded the capabilities of electric actuators. They are now commonly used in fields such as aerospace, robotics, renewable energy systems (like solar panel tracking), and precision manufacturing, where clean, programmable, and reliable motion control is essential [1].

5.4 Key application of electric actuators

Electric actuators are one of the main components of automated equipment used in today's factories. Servo rotary actuators with 0.01° repeatability are used extensively by robotic production lines for precision part location and laser welding. Linear electric actuators are particularly popular with the auto industry for panel-stamping presses with 50 kN forces required with ± 0.1 mm position precision. Semiconductor production uses piezoelectric actuators for wafer steppers with nanometric precision in photolithographic processing. Electric actuators consume up to 60% less energy than traditional pneumatic drives under continuous operation with built in sensors giving the added benefit of data monitoring.

Electric actuators have become very used and important in the medical field. Robots in surgery, like the da Vinci surgical robot, utilize the application of direct drive torque motors with 0.01 Nm of sensitivity for stable movement. Miniature force-sensing linear actuators are utilized by prosthetic limbs for movement in a very natural manner with myoelectric control. Medical imagers utilize piezoelectric actuators for exact positioning in MRI and CT scanners so that they are able to make high-resolution diagnosis.

Electrification of transportation industries has driven the implementation of electric actuators. Power steering with electric motors replaces hydraulic with 300W brushless DC motors. Electric actuators are utilized in autonomous cars for brake by wire and throttle application where there needs to be less than 50ms response time for collision avoidance. Electromechanical actuators are utilized for suspensions and tilting on high-speed trains where reliability demands more than 1 million execution cycles. On top of that as already known electric cars being powered by electric motors as well as hybrids are going to be the most important engineering part, so with that future and modern engineering is hard to imagine without electric actuators.



(a) Industrial elec motor



(b) Electric car powered by electrical motors

Figure 9: Examples of electircal actuators and their use

6 Comperative analysis

The selection of actuation technology represents a critical decision in mechanical system design, with hydraulic, pneumatic, and electric systems each offering distinct advantages and limitations. This comprehensive analysis examines these three principal actuation methods across multiple performance parameters, drawing upon recent research findings and industrial case studies to provide a rigorous comparison. The evaluation considers force capacity, energy efficiency, control precision, maintenance requirements, environmental impact, and total cost of ownership to establish clear guidelines for technology selection in various application scenarios. Hydraulic systems maintain undisputed dominance in high-force applications, with industrial hydraulic cylinders routinely generating forces exceeding 500 kN in heavy press machinery [1]. The incompressibility of hydraulic fluids enables power densities up to 10 MPa, allowing compact actuators to handle extreme loads. Recent electro-hydraulic hybrid designs have further enhanced this capability while improving energy efficiency[1].

Pneumatic actuators operate in a moderate force range (typically 10 N to 50 kN), limited by practical air pressure constraints of 0.6-1.0 MPa. Their lightweight construction enables rapid acceleration, with some pneumatic grippers achieving 10 m/s² acceleration rates [5]. However, air compressibility introduces non-linear force characteristics that complicate precise force control.

Electric actuators have seen significant force capability improvements, with modern ball screw designs reaching 200 kN in large linear actuators. While still trailing hydraulics in maximum force output, electric systems excel in force control precision, maintaining $\pm 0.5\%$ force accuracy even at minimum loads [4]. Direct-drive rotary motors now achieve torque densities rivaling hydraulic motors in the 50-500 Nm range.

The energy efficiency landscape reveals stark contrasts between technologies. Electric servo systems lead with 85-95% energy conversion efficiency, benefiting from regenerative braking capabilities that recover energy during deceleration [1].

Hydraulic systems suffer from multi-stage energy losses, with typical system efficiencies of 40-60%. Pump losses, throttle valve losses, and leakage collectively degrade performance, though variable displacement pumps and accumulator systems can improve this to 70% in optimized designs [5]. The continuous operation of hydraulic pumps represents a significant energy drain, even during idle periods.

Pneumatic systems exhibit the poorest energy efficiency (30-50%), primarily due to air compression losses and exhaust energy waste. Research indicates that up to 90% of input energy converts to heat in pneumatic systems, with only 10-20% performing useful work [4]. However, their intermittent duty nature in many applications partially mitigates this disadvantage.

When comparing the performance characteristics, it becomes clear that hydraulic actuators dominate in force output and load handling, making them the best option for heavy lifting and industrial pressing tasks. Pneumatic actuators, while less powerful, excel in speed, safety, and simplicity, especially for short-stroke and repetitive motion tasks. Electric actuators, meanwhile, offer the most precise and programmable control, making them ideal for applications requiring complex motion patterns, frequent adjustments, or integration with automated control systems. In terms of energy efficiency, electric actuators clearly outperform both hydraulic and pneumatic options, as they

draw power only when motion is required, whereas the other two often require continuous energy input to maintain pressure. Regarding maintenance, electric actuators again take the lead due to their sealed and self-contained design. In contrast, hydraulic and pneumatic systems are more prone to wear, leaks, and environmental contamination, resulting in higher upkeep demands.

In terms of environmental impact, electric actuators are by far the most sustainable option. They eliminate the need for oil or compressed air and contribute significantly to cleaner working environments and lower operational emissions. As industries aim for greener operations, electric actuators are being used more frequently to replace hydraulic and pneumatic systems, particularly in applications that benefit from smart integration and lower carbon footprints. As discussed in several of the articles you provided [3], there is ongoing research into replacing hydraulic fluids with more eco-friendly options, but even then, the risk of leakage and contamination remains a concern for hydraulic setups.

Ultimately, the choice between these actuators depends on a complex balance of factors: the nature of the task, the environment, required precision, force, cost, and long-term sustainability. In high-force applications with harsh environments, hydraulic systems remain the top choice. For rapid, safe, and cost-effective motion with moderate force requirements, pneumatics are widely preferred. And in precision-driven, data-integrated systems, electric actuators are unmatched. The future of actuation likely involves hybrid systems and innovations that combine the strengths of all three types. For example, electromechanical actuators that mimic hydraulic performance or pneumatic systems with advanced electronic feedback are already under development. As research and technology continue to evolve, particularly with the integration of AI, IoT, and green energy solutions, the roles of these actuators will continue to shift—pushing the boundaries of automation, control, and environmental responsibility.

Table 1: Comparison of Hydraulic, Pneumatic, and Electric Actuators

Category	Hydraulic Actuators	Pneumatic Actuators	Electric Actuators
Working Principle	Use pressurized, incompressible fluid (oil) to move a piston or motor.	Use compressed air to move a piston or vane.	Use electric motors (servo, stepper, AC/DC) to generate motion.
Force Output	Very high (hundreds of kN). Best for heavy-duty applications.	Moderate (up to 50 kN). Limited by air pressure.	High precision; improving force (up to 200 kN) but less than hydraulics.
Speed	Moderate, depends on system size and valves.	Very fast motion, ideal for rapid cycles.	Moderate to fast, depending on motor and control system.
Control Precision	High with advanced valve systems but generally moderate.	Limited precision due to air compressibility.	Very high precision and programmability.
Energy Efficiency	40–60% (losses due to pumps, leaks).	30–50% (most energy lost as heat during air compression).	85–95% (most efficient, regenerative braking possible).
Maintenance	High; prone to leaks, contamination, requires regular service.	Moderate; leaks and air losses are common, but simpler design.	Low; minimal moving parts, no fluid handling.
Environmental Impact	Risk of fluid leaks; environmental contamination concerns.	Clean (uses air), but inefficient energy use.	Clean, no emissions or fluids; best for sustainable applications.
Cost	High initial cost; maintenance costs add over time.	Low to moderate; operational cost depends on air management.	Moderate to high initial cost; lower operational cost.
Key Applications	Heavy machinery, aircraft systems, industrial presses, ship systems.	Automation lines, packaging, food processing, light handling robots.	Robotics, medical devices, precision manufacturing, electric vehicles.
Advantages	Extremely high force, durability under harsh conditions, precise heavy load control.	Simple, fast, safe in explosive environments, clean for sensitive industries.	High precision, clean operation, easy integration into digital control systems.
Disadvantages	Heavy, complex, energy-inefficient, environmentally risky.	Poor force control, low energy efficiency, less precision.	Lower force limit, heat issues under continuous use, electrical safety concerns in hazardous areas.

7 Conclusion

In conclusion, the comparative study of hydraulic, pneumatic, and electric actuators reveals that no single actuation system is universally superior; instead, each type possesses unique advantages and limitations that make it more or less suitable for specific applications. Hydraulic actuators are unmatched when it comes to delivering high force and torque, making them ideal for heavy-duty tasks in industries such as construction, mining, and manufacturing. However, their environmental drawbacks, maintenance complexity, and susceptibility to leakage limit their use in modern, sustainability focused applications. Pneumatic actuators, valued for their speed, simplicity, and safety, excel in environments where rapid, repetitive motion is needed and where cleanliness is crucial such as in food processing and light automation. Yet, their imprecise control and energy inefficiency due to air compressibility can pose challenges in high performance settings. Electric actuators stand out in terms of precision, control, energy efficiency, and seamless integration with digital systems. They are increasingly becoming the preferred choice in advanced automation, robotics, aerospace, and medical technology, particularly where accurate, programmable, and maintenance-free operation is essential.

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