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LINEAR MOTION MINIATURE ACTUATORS

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Abstract

The objective of the paper is to give an overview of linear motion miniature actuators and different actuator technologies today. Miniature refers to devices with dimensions smaller than ten centimeters and actuating precisions in micrometer range or smaller. We have noticed that there are only a few linear actuators that have small size, high resolution and long total displacement at the same time. This is understandable because in most cases these demands limit each other. Basic actuator technologies like electromagnetic, piezoelectric, electrostatic, shape memory, magnetostrictive, and electrorheological are shortly discussed. Most applications today are based on electromagnetic or piezoelectric principles.

Keywords: linear actuators, miniature

1 Introduction

Miniaturization has been one of the most important technological trends in the last decades. Microelectronics has paved the way. The sizes of chips have been reduced from centimetres to micrometers, and very high component densities have been achieved. It is expected that electromechanical systems will develop in the same way. The successful fabrication and operation of actuators and mechanical devices provide the opportunity to produce miniature machines and small mechanical systems. In today 's devices the most compact and smallest part usually represents the most advanced intelligence. Good examples are cards in mobile phones and processors in computers. They control the process by "passive movements". If we go one step further by adding active movements the complexity increases. We need a device, an actuator, that transforms electrical signals into controllable motion.

When choosing an actuator the importance of the needed functions should be specified. First of all it has to be found out, whether the motion is rotational or linear. Other properties that have to be taken into account are precision, speed, shape, torque or strain. In today's commercial products certain properties are emphasized. For example they offer either high resolution or long total travel. This is typical of linear actuators, especially small ones, and they lack at least one of needed properties. The basic actuator technologies set, of course, limits and therefore actuators have been created by mixing technologies and properties. In this paper both actuator technologies and linear actuator solutions are discussed.

2 Electromagnetic actuators

Electromagnetism arises from electric current moving through a conducting material. Attractive or repulsive forces are generated adjacent to the conductor and are proportional to the current flow. Typical examples that use electromagnetic principle are electric motors, solenoids and voice coil actuators.

2.1 Electromagnetic motors

In conventional motor solutions the motion is transferred to linear by combinations of screws and nuts. Also ball bearings and roller screws are generally used. The accuracy depends on the used pitch and the used support. The support helps us to get rid of axial play. Gears are generally used in both DC and stepper motors. For example in a DC motor we can improve the accuracy by using for example a reduction gear and an encoder. The reduction gear increases also the torque but sacrifices the speed [1]. Suppose that an angular encoder provides a resolution of 400 steps per revolution and the ratio of the reduction gear is 100:1. By using a spindle with 1 mm pitch we can achieve theoretically a resolution of 25 nanometer [2]. In practice the accuracy is decreased by the backlash of the gear and radial play of the shaft. Therefore the movement should be measured, if possible, with a sensor directly from the part moving axially.

Stepper motors are usually used open loop without encoders, because they are driven one step at a time. If there are any positional errors between steps they are typically in the range below 0.1 degree. The error is not accumulating during the motor's revolutions [3]. Stepping motors can loose steps because of too large a load. Stepper motors are usually possible to be driven by microstepping, which improves the resolution. Therefore they are suitable for applications where high speed is needed and the loads are small [1].

Wittenstein GmbH has developed roller screws where the motion is transmitted between the screw shaft and nut by means of rolling elements (figure 1). Both fine and coarse grooves are cut into the rolling elements. The nut has coarse grooves that support the rollers and the shaft has fine grooves that match the rollers' fine grooves. By this the rollers and the nut always move in the axial direction at same speed and we get a smooth and precise movement without mechanical backlash.

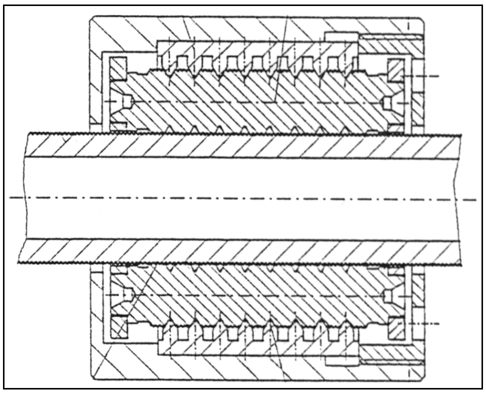

Figure 1. Wittenstein roller screw [4].

A disengaging and return mechanism or geared drive for the rollers is therefore not needed. The resolution depends on the used pitch. Wittenstein offers screw shafts with extremely small pitches, 0.1 mm. Other advantageous features are quiet movement and large power increase [4].

In opposite to rotational the linear stepper motors operate in a straight line on a fixed base. The Haydon Switch and Instruments offers linear stepper motors that move in linear increments of tens of micrometers. In figure 2 is HSI (Haydon Switch and Instrument) bipolar linear stepper motor. Bipolar drive means that the current can be driven in either direction through each coil, in other words the polarity can be changed [1]. This increases the coefficient of efficiency and widen the control possibilities. The shown motor has 12 micrometer resolution and even 10 mm total displacement [5]. The size of the motor is relative small to be a linear motion device. It's possible to drive the motor by microstepping, which improves the resolution.

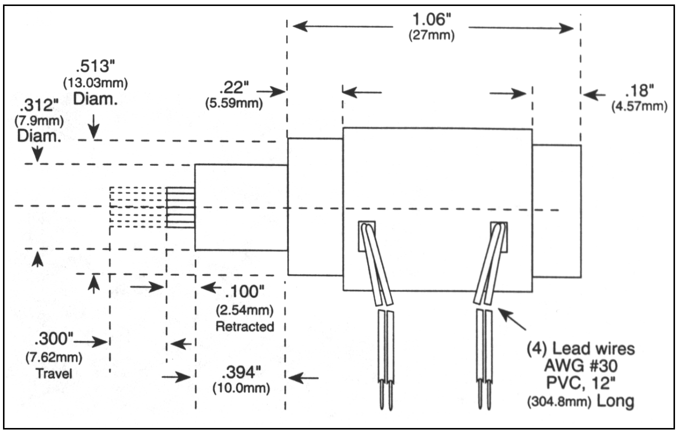

Figure 2. HSI linear stepper motor [5].

Microstepping is a technique that divides each full step of the motor into smaller steps. If the windings phase currents next to each other are unequal, the rotor position will be shifted towards the stronger pole. This is utilized in microstepping drive, which subdivides the motor step by proportioning the current in the windings. By varying the current differencies one step can be divided up to 500 steps, which makes 100 000 microsteps per revolution possible [1].

Certain direct drive motors operate in a similar manner as stepper motors. But in direct drive systems the load is directly coupled to the motor without the use of belts or gears [1]. Without gear the size is smaller and the friction is better eliminated. In direct drives the feedback element can be directly coupled to the load, which improves accuracy and repeatability of the system.

In generally motors can offer solutions where micrometer resolutions in linear motions can be achieved, but unfortunately the size of the system grows too big.

2.2 Solenoids

Solenoids use a coil of wire to generate a magnetic field that attracts an iron component toward the coil. A typical solenoid is shown in figure 3. The force generated by the solenoid is a function of the number of turns N of the coil, the current I, the pole area A, the air gap h, and magnet permeability of air μ [6]:

$$F = \frac{N^2 I^2 A\mu}{2h^2} \tag{1}$$

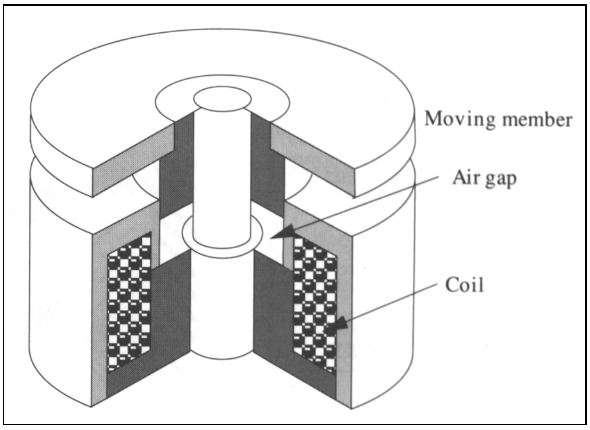

Figure 3. Solenoid [6].

Since solenoids are dependent on the coil to establish the magnet circuit, they have a slow electromechanical time constant. Therefore solenoids are often used as cheap solutions in mechanical stops.

2.3 Voice coil actuators

Voice coil (wound coil/moving coil) actuators use permanent magnets to establish a magnetic circuit. A current applied to the coil produces a change in the magnetic field and force on the coil. The force is proportional to the permanent magnet's magnetic field B, the length l of the moving coil, the current i, and the number of turns N:

$$F = BliN \tag{2}$$

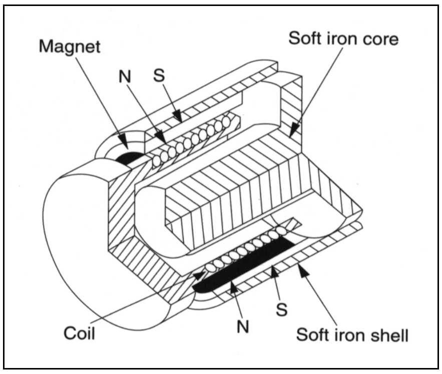

Figure 4. Voice coil actuator [7].

The coil is often used as the moving member because it usually has a lower mass than the magnet assembly (figure 4). Moving coil actuators provide larger forces than solenoids, but they are on the other hand more expensive. The voice coil actuators have zero mechanical hysteresis (but they do have magnetic hysteresis), zero force or torque ripple, and zero backlash. If the manufacturer has succeeded in supporting the core the precision of the movement is more dependent on the sensor and the servocontroller [6]. Thus nanometer resolutions are possible with voice coil actuators, over a range of many millimeters. Commercial products are available for instance from BEI Sensors & Systems

Company [7]. Their principal drawback is that they can generate considerable heat. They have been used for instance as positioners in computer disk drive heads and in mirror systems.

3 Piezoelectric actuators

The piezoelectric phenomenon was observed in 1880. Certain types of crystals develop an electrical charge when exposed to mechanical stress. Conversely, the application of an electric field to a piezoelectric crystal leads to a physical deformation of the crystal. Piezoelectric ceramics must undergo a polarizing process for the piezoelectric phenomenon to occur. As a result, the piezoelectric effect is much stronger.

PZT is the dominant piezoelectric ceramic and it is widely used in piezoelectric actuators. Two types of PZTs are available: high-voltage PZT and low-voltage PZT [8]. The low-voltage (LV) element operates in the voltage range of 0 - 100 V, while the high-voltage (HV) element requires an operating voltage of up to 1000 V. By reducing the layer thickness in the LV element the distance between the electrodes shortens, thus decreasing the required voltage. The properties of LV elements differ slightly from those of HV elements.

Piezo actuators can provide extremely fine resolution depending only on the power supply. Unfortunately, the displacement of a PZT is not ideal, but includes hysteresis, drift and thermal variations. When the operating voltage of a PZT is set to a new value, the length of the element slowly drifts after the actual dimensional change. However, drift and hysteresis can be eliminated using position feedback. In addition to the thermal heat expansion, temperature affects the piezoelectric effect. Moreover, operation close to Curie temperature depolarizes the material reducing the expansion capacity.
The maximum expansion of the piezoelectric element depends on its material and length, and the applied electric field and force. The widely used formulas describing piezoelectric behaviour are [9]

$$S = s^E \cdot T + d \cdot E \tag{3}$$
$$D = d \cdot T + \varepsilon^T \cdot E \,,$$

where S represents the strain tensor, s^E is the elastic compliance at a constant electrical field, T represents the stress tensor, d is a piezoelectric material constant, E is the electric field, D the electric displacement and ε^T the permittivity at a constant stress.
The piezoelectric actuators provide good resolution, small stroke, high speed, high output force and low power consumption. Conventional piezos' resolution is typically below one micrometer, but even one nanometer is possible. The very small total strokes are the drawbacks of piezos. Other advantages of piezomaterials are their mechanical durability. Several designs are used in piezoelectric actuators: stacked design, extender design, tube design, bimorph design and hybrid design (figure5).

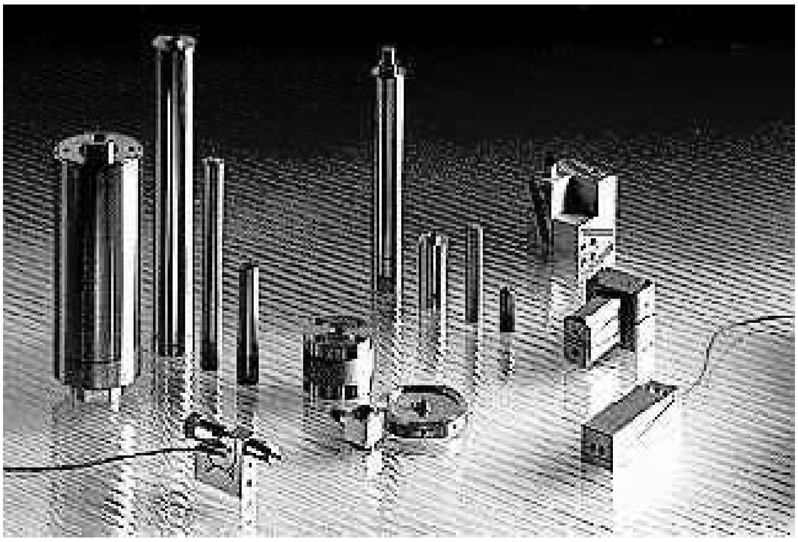

Figure 5. Different piezo actuators [8].

3.1 Stacked Design

In stacked piezos each ceramic disk lies between two electrode surfaces. The thinner the disk is, the higher the field strength is and therefore the relative change in length is greater. Stacked piezos are one example of how piezos' displacement is magnified. The thickness of a disc varies from 0.1 mm to 1 mm. The stacked elements have a great ability to withstand pressure and stiffness. Moreover, they have high output force, good resolution and high speed of response.

3.2 Laminar design

Laminar type of actuators are made of flat strips arranged in parallel. Unlike the stacked actuators, the expansion is perpendicular to the direction of polarization. The maximum expansion in the strip design is proportional to the length of the strips, while the number of the strips affects the stability and the stiffness of the structure. The stroke of the strip type of actuator is smaller than that of the stacked structure.

3.3 Tube design

Tubes and rings are also used as piezotranslators. If a voltage is applied between the external and internal walls of the piezoelectric tube, the length of the tube changes. Several tubes cannot be used in parallel and the structure is therefore limited to thin walls. For this reason the tube design cannot be manufactured for large loads. Tubes offer no advantages and are therefore seldom used in applications. Rings are made from disks and can therefore have thicker walls.

3.4 Bimorph design

The bimorph is similar to a bimetallic gauge, two thin ceramic strips are connected together so that one of them contracts while the other expands. There are also designs where one PZT strip and a steel strip are bonded together. Bimorphs are usually mounted as a cantilever. When a voltage is applied, the cantilever deforms. The output movement of the bimorph actuator is large, but the force is small. For this reason, actuator applications are not common. Much better properties are achieved by bimorph constructions in disk translators. A piezoelectric disk is attached to a metal disk of the same size. When an operating voltage is applied, the centre of the piezo disk arches up.

3.5 Hybrid design

Since the movement of the piezoelectric actuators is small, displacement amplifier of some sort is needed. Amplification techniques used can be categorized into five groups [10]:

- lever systems
- hydraulic systems
- impulse transfer systems
- integration systems
- composite systems

Lever systems utilize lever arms of dissimilar lengths to magnify the displacement. The output force of the lever system is remarkably lower than the output force of the actuator inside the system. In hydraulic systems the amplification is typically achieved with piston and bore assemblies. In impulse transfer systems the magnification is based on rapid deformation of the multilayer device. In integration systems the large movement is achieved by several small steps. Inchworm and ultrasonic motors fall into this group. Composite designs that combine several basic designs are also included in the hybrid designs. Next some special cases are presented that are closely related to the groups mentioned above.

In **inchworm motors** (Burleigh) the movement along a rod is achieved by using three piezoelements, as shown in figure 6. The outer elements act as clamps, while the central element creates the actual motion in discrete steps along the shaft. When a voltage is applied to element 1, it grips the shaft. Then a voltage is applied to the central element deforming it in the steps of nanometer resolution. At the end a voltage is applied to the element 3 and removed from the element 1. The staircase voltage is now driven downwards until the element 2 reaches its initial length.

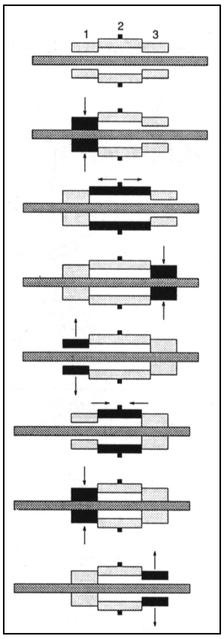

Figure 6. Inchworm motor operation [11].

Then the element 1 is clamped, the element 3 released and the sequence starts again. By this we get a movement that actually can be unlimited. The operating principle of the Inchworm Motor facilitates not only a good resolution but also a large maximum displacement. Internal encoders can be used. The maximum speed is about 2 mm / s [11]. The drawback of the Inchworm Motors is their high price.

The operating principle of the **ultrasonic motors** lies in the generation of a travelling wave on a body [12]. The particles on the surface move along elliptical trajectories. The motion of the particles is in the opposite direction of the wave. When a moving body is placed on the surface, it moves in the direction of the particle motion. The elastic body is typically attached to piezoelectric ceramics. The piezoelectric disc that basically produces the travelling wave can be made for example of several elements polarized in opposite directions. This kind of structure has been designed by Matsushita Electric [12].

Dogan et al. [13] at the Pennsylvania State University propose a composite actuator that combines stack design and bimorph design. The actuator that they call the "**moonie**" is composed of a multilayer piezo actuator and two metal strips. The piezo actuator is sandwiched between the strips having shallow cavities. The metal strips serve as mechanical transformers for converting and amplifying the lateral movement of the stack into an axial movement. The displacement is affected by the cavity size, and the thickness and the material of the strips. Higher displacements are achieved by stacking several moonies together. Recently Dogan et al. have improved the design. New designs using truncated conical metal endcaps, called "cymbals" have demonstrated even higher displacements [14].

The **Rainbow piezodisc** reminds the previous one. The Rainbow actuator is structurally similar to unimorph type of elements. The actuator is a single element structure consisting of a PZT side and a metallic side [15]. One side of the circular shape wafer is in tension and the other in compression forming a domed structure. When a voltage is applied opposite to the poling field, the wafer buckles and when the voltage is parallel to the poling field, the wafer straightens. The whole area moves but the motion is more pronounced at the centre. The actuator provides larger strain than for example multilayered piezo actuators but it is somewhat slower and produces smaller output force.

The authors have developed a **piezohydraulic actuator** by combining a nickel bellows with the Rainbow piezodisc [15]. The actuation system consists of the piezoelectric actuator, a small tank and the bellows, as illustrated in figure 7.

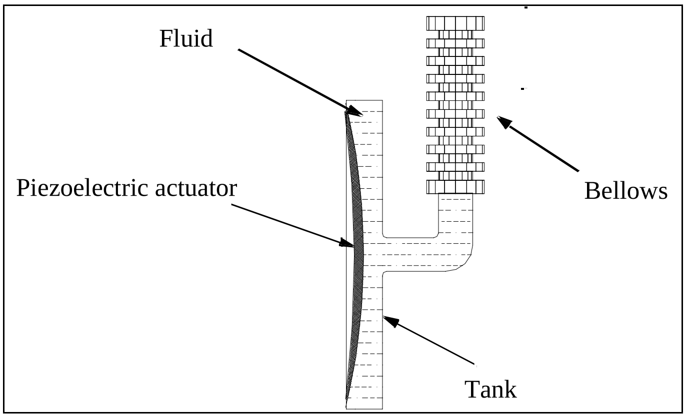

Figure 7. The actuation system.

The piezo actuator is placed in the tank filled with hydraulic oil. When a voltage is applied to the actuator, it deforms. When the actuator buckles, oil flows from the tank to the bellows which elongates, and vice versa, when the actuator gets straightened, oil flows from the bellows to the tank. Since the effective area of the bellows is smaller than that of the actuator, the displacement is magnified. Pistons or valves are not needed, which results in a very simple structure and decreased problems with sealing. The results of displacement experiments have shown that the movement range of the actuator is about ± 250 µm (maximum displacement 500 µm).

One idea is also to use a linear stepping motor to carry a ring piezo on its moving shaft. The motor take care of the macromovement and the piezo makes the micromovement. The size of the system remains small as the piezo is attached to the shaft.

4 Electrostatic actuators

The origin of the electrostatic actuation lies in the Coulombic force: the attractive force between two conductive plates with unlike charges. When a voltage is applied between the plates, the attractive force F_N is exerted on the plates:

$$F_N = \tfrac{1}{2}\varepsilon A\left(\frac{U}{d}\right)^2 \tag{4}$$

ε is the dielectric constant
A is the area of the electrode
d is the distance between the electrodes
U is the operating voltage

The field strength depends on the gap size as well as surface roughness. Therefore, even a dust particle can cause a breakdown due to a small air gap. Electrostatic fields can exert great forces, but generally across very short distances. A small stroke is as well a limitation of linear electrostatic actuators. Thus, multilayered structures have to be used. As the electrostatic force depends on the opposing surfaces and the distance between them, makes it well suited for the micro world. The most electrostatic actuators are still at research level.

5 Electrostrictive actuators

Electrostriction refers to deformation of the material in an electric field. Commercial actuators based on electrostrictive crystals are available. Electrostrictive polymers have been investigated to generate muscle-like actuation.

Electrostrictive crystal actuators use the stack design where the displacement is a superposition of the strain from several thin crystal layers. Unlike piezoelectric ceramics, for example PZT, electrostrictive crystals are not poled. Positive or negative voltage results in a displacement in the direction of the applied electric field, regardless of the polarity. The strain of the electrostrictive ceramics is in the same order as the strain of the piezoelectric ceramics. However, the electrostrictive ceramics provide better characteristics of hysteresis and creep. But their strain sensitivity to temperature is much higher.

Elastomeric dielectric actuation has been studied at SRI International, USA. Their basic functional element is a thin elastomeric polymer film sandwiched between electrodes [16]. When a voltage is applied to the electrodes, electrostatic force compress and stretch the film. Like the piezoelectric element, the basic element of the elastomeric actuation can be used in different designs. Film layers may be actuated in stacks, extenders, tubes or rolls.

6 Magnetostrictive actuators

A ferromagnetic crystal changes its shape when subjected to a magnetic field. This effect is called magnetostrictive effect, discovered 1842 by Joule [17]. The longitudinal magnetostriction, i.e. the change in the length is utilized in actuator applications. Among the magnetic materials Terfenol-D has been the most widely used in magnetostrictive actuators as a highly magnetostrictive material. The actuator is typically composed of a magnetostrictive rod placed inside a coil. When a magnetic field is not applied, the magnetic domains orient randomly in all directions. A current inside the coil produces a magnetic field that elongates the rod, as the magnetic domains are arranged in the direction of the magnetic field. The main disadvantage of magnetostrictive actuators are their small displacements. In some solutions the magnitude of the strain has been about two times larger than the strain of a stacked piezoelectric actuator [18]. Magnetostrictive actuators offer very large output forces and quick dynamic responses.

7 Shape memory alloys

When a shape memory alloy is deformed in the room temperature and heated after that, the SMA tends to return to its original shape. This is called a shape memory effect. The original shape is defined, stored into the memory of the material, over a tempering process. At high temperatures a shape memory alloy is like any metal and has a high strength [19]. When the material is cooled below a specific transformation temperature, its crystalline phase change and the material becomes soft and can be easily deformed. In the plateau region large strains can be achieved with a small change in stress. But if the deformation exceeds the second leap point, the material loses its shape memory effect. When the sample is heated up again, it returns to its original shape above a transformation temperature. The most widely used shape memory alloy is Nickel Titanium alloy. Shape memory alloys have a large strain compared with piezoelectric materials. The recovery strain is in the order of 8 %, but to be used more than a few cycles the strain should be below 5 %. The strain can be detected for example by measuring the change of resistance, which is the most linear method. The main disadvantage is the slow speed of response. However, the heating and cooling rates increase, when the size of the actuator decreases. Therefore, the smaller the size of the actuators the faster it is.

8 Other actuators and phenomenon

Hydraulic actuators are typically large in size, but they are good in applications where strong forces are needed. Although one does not normally think of hydraulic systems as being able to provide precise position sometimes hydraulic actuators could be superior to other types because they can have zero friction and nearly backlash free power transmission [6]. There are small sized piston and rod systems with special seals and coatings. For instance teflon is widely used. Another component that is used is metallic bellows. They are seamless, frictionless and they transmit the hydraulic movement into linear. The properties of the used liquid are of course also important.

Hydraulically or pneumatically driven **rubber actuators** have also been studied for example to be used in artificial muscles.

Different kinds of fluid phenomena have also been utilized in actuators. The form of an **electrorheological fluid** changes when it is placed in an electric field [20]. Depending on the strength of the electric fluid, the electrorheological fluid acts like water, honey or metal. Electrorheological fluids respond very quickly; they can switch from one state to another in milliseconds. Electrorheological fluids consist of micro-sized particles suspended in a dielectric liquid. The actuating system based on electrorheological fluids can be kept very simple - only fluid and electrodes are needed - and a high band width can easily be achieved. However, they suffer from several problems, such as weakness as solids and chemical instability. Consequently, although many companies are researching electrorheological fluids, none are in commercial production.

Magnetorheological fluids act very much like electrorheological fluids, except that their flow rate is controlled by the strength of a magnetic field, instead of using an electric field.

9 Conclusion

There are a number of actuator alternatives for linear motion. However it is difficult to find solutions that have small size, high resolution, and long total displacement at the same time. This is understandable because in most cases these demands limit each other. Linear electromagnetic motors are often too large in size. Piezoelectric and magnetostrictive actuators are capable of only small strains. Shape memory alloys and polymers are slow, and electrostatic actuators require high operating voltages. Presently, commercial microsensors are ahead of micro- and miniature actuator technologies. But it is expected that the actuator technology will develop together with advances in electronics.

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