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Actuators in motion control systems: mechatronics

Actuators are irreplaceable constituents of mechatronic motion control systems. Moreover, they are true mechatronic systems: that is, concurrent engineering is required to fully exploit their potential as actuators.

This chapter analyzes the actuator as a device included in motion control systems. It introduces the intimate relationship between transducers, sensors and actuators, and discusses the implications of sharing these functions on the same component.

It also discusses the role of the actuator as a device establishing an energy flow between the electrical and the mechanical domain, and it introduces a set of relevant performance criteria as a means for analyzing the performance of actuators. These criteria include both static and dynamic considerations, and also the performance of the actuator technology upon scaling.

Actuators are classified into active and semiactive actuators according to the direction in which energy flows through the actuator. Active technologies (Piezoelectric, SMA, EAP and magnetostrictive actuators) are then discussed in Chapters 2 through 5, and semiactive technologies (ER and MR actuators) in Chapter 6.

Finally, after explaining the distinction between emerging and traditional actuators, this chapter concludes with an analysis of other actuator technologies (electrostatic, thermal and magnetic shape memory actuators) not specifically dealt with in separate chapters.

1.1 What is an actuator?

The mechanical state of a system can be defined in terms of the energy level it has at a given moment. One possible way of altering the mechanical state of a system is through an effective exchange of energy with its surroundings. This exchange of energy can be accomplished either by passive mechanisms, for example, the typical decaying energy mechanism through friction, or by active interaction with other systems. An actuator is a device that modifies the mechanical state of a system to which it is coupled.

Actuators convert some form of input energy (typically electrical energy) into mechanical energy. The final goal of this exchange of energy may be either to effectively dissipate the net mechanical energy of the system, for example, like a decaying passive frictional mechanism, or to increase the energy level of the system.

An actuator can be seen as a system that establishes a flow of energy between an input (electrical) port and an output (mechanical) port. The actuator is transducing some sort of input power into mechanical power. The power exchange both at the input and output ports will be completely defined by two conjugate variables, namely, an effort (force, torque, voltage etc.) and a flow (velocity, angular rate, current, etc.). Eventually, some input power will be dissipated into heat. See Figure 1.1 for a schematic representation of the actuator.

The ratio of the flow to the effort (conjugate variables) is referred to as *impedance*. If an electrical input port is considered, the voltage and the current drawn will completely define the power flowing in the actuator, and the ratio is the familiar electrical impedance. By analogy to the electrical case, at the mechanical port, the ratio of flow (velocity or angular rate) to effort (force or torque) is referred to as *mechanical impedance*, and both variables will define the power coming out of the actuator.

The concept of power exchange at the input and output ports of an actuator gives rise to a wider definition of actuators as devices whose input and output ports exhibit different impedances. In general, neither the input electrical impedance of an actuator will match that of the controller nor the output mechanical impedance will match that of the driven plant. This lack of match between input and output

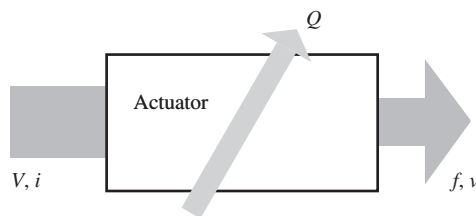


Figure 1.1 Actuator concept: energy flows from the input to the output port. Eventually, some energy is dissipated (undesired losses).

impedances means that impedance adaptation is required both at the input and output ports. The issue of impedance matching will be dealt with in more detail in Section 1.3.

Actuators are most often found in *motion control systems*, (*MCS*). In these systems, the ultimate objective is to drive the plant along some reference trajectory. The role of the actuator in such a system is to establish the flow of power by means of some control actions (inputs) in response to process models or sensory data so that the desired trajectory is effectively accomplished.

The dynamic interaction between the actuators and the controlled system can be defined according to the magnitude of the energy being exchanged, $dW = F \cdot dX$, Hogan (1985a). In some particular situations, the instantaneous energy exchange can be ignored. This is the case where the force or the displacement is negligible. On the one hand, if the force is zero ($F = 0$), the system can be considered position controlled. On the other hand, wherever the displacement is zero ($dX = 0$), the system is force controlled.

In general, the interaction will take place with a finite, nonzero instantaneous energy exchange ($dW \neq 0$). In such a case, the motion control system will be able to impose the effort (force, torque), the flow (velocity, angular rate), or the ratio between them (the impedance), but not both simultaneously.

Depending on the sign of the admissible instantaneous work exchange, dW , actuators can be classified as:

1. *Semiactive actuators*: the work exchange can only be negative, $dW \leq 0$. In practice, this means that semiactive actuators can only dissipate energy as a consequence of mechanical interaction with the controlled system. These actuators are dealt with in Chapter 6.
2. *Active actuators*: the work exchange can take any positive or negative value, $dW \leq 0$. For practical purposes, this means that active actuators can either increase or decrease the energy level of the controlled system.

The ultimate constituent of an actuator is the transducer. A transducer has been defined (Middlehoek and Hoogerwerf (1985)) as *a device, which transforms nonelectrical energy into electrical energy and vice versa*. This definition of a transducer emphasizes the fact that most actuators (transducers) are driven by logic elements in which the information flow is electronically established. As such, transducers ultimately transform to and from electrical energy.

Transducers have also been defined (Rosenberg and Karnopp (1983)) as *devices, which transform energy from one domain into another*. Rosenberg's definition of a transducer is broader than the previous one since it does not restrict transduction to or from the electrical domain. Finally, the broadest definition of a transducer makes a distinction between different types of energy within a single domain (differentiating between rotational and translational mechanical energy). It states (Busch-Vishniac (1998)) that a transducer is *a device, which transforms energy from one type to another, even if both energy types are in the same domain*.

A transducer can be used to monitor the status of a parameter in a system, or it can be used to define the status of such a parameter. It is the former use of transducers that produces the *concept of sensors*. A sensor is thus a transducer, which is able to monitor the status of a system (ideally) without influencing it.

On the other hand, an actuator can be defined as a transducing device, which is able to impose a system status (ideally) without being influenced by the load imposed on it.

The transduction process can be established between any two energy domains (see second definition of transducers) or even between different energy types within the same domain (see third definition). Whenever a transducer is used to impose a status on a system (actuator concept), such wide definitions of transducers would include actuators capable of establishing energy flow between any two energy domains. Throughout this book, the first definition of transducers is used and is restricted to output mechanical energy.

A transducer might establish energy flow between nonelectrical input energy domains and output mechanical energy – see the case of a thermally actuated shape memory alloy (SMA) transducer. For practical purposes, it is always possible to include any subsystem in charge of electrically driving the transducer in the actuator system. This applies, for instance, to electrically heating the SMA transducer by means of a Joule effect (delivering heat through resistance heating). The actuator system as a whole establishes a flow of energy between the electrical domain and the mechanical domain (see Figure 1.2).

The use of electrical energy at the input port of actuators has clear advantages:

1. *Compatible energy domains.* Most motion control systems (in which actuators are usually included) are controlled electronically; thus, the output energy domain of the control part is already in the same energy domain as the input actuator port.
2. *Fast operation of electric devices.* Electronic and electric devices are characterized by fast operation, in most cases much faster than the intrinsic time constants of the actuator. This improves the controllability of actuators.
3. *Availability of components.* The electronic components used in the control and conditioning system are well-known and readily available.

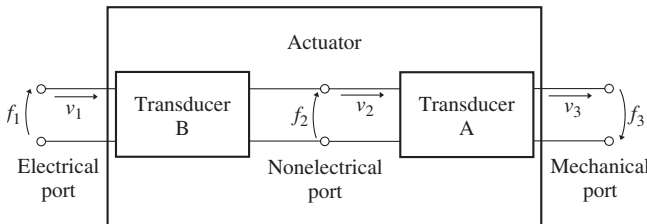


Figure 1.2 Actuator concept as a two-port transducer: input electrical port and output mechanical port.

In view of the above considerations, the actuator concept that we will use throughout this book comprises both the transducer itself (possibly between non-electrical domains and the mechanical domain) and the subsystems responsible for electrically driving the transducer. Note that the subsystems used for electrically driving the transducer could, in turn, be considered an additional transducer, according to the broad definitions noted earlier (see transducer B in Figure 1.2).

1.2 Transducing materials as a basis for actuator design

Transduction is the process of energy conversion between either different energy domains (for instance, from thermal to mechanical energy) or different energy types within the same domain (for instance, between rotational and translational energy). A more restrictive definition of transduction defines the input domain as electrical energy and the output domain as mechanical energy.

The transducer is the device in which transduction is accomplished. In general, two types of transducers can be considered (Busch-Vishniac (1998)):

1. *Geometrical transducers.* In geometrical transducers, the coupling between input electrical energy and output mechanical energy is based on the exploitation of some geometrical characteristics. Actuators resulting from geometrical transducers are called by extension *geometrical actuators*. This applies to all rotational actuators.

In particular, if a rotational permanent magnet electromagnetic DC motor is considered, the geometry of the magnetic flux with regard to the configuration of the current flowing in the coils leads to a Lorentz interaction, which, in turn, results in a rotational motion of the coil (see Figure 1.3).

2. *Transducing materials.* A transducing phenomenon between any of the different energy domains is directly exploited to develop actuators. Examples include stack piezoelectric actuators or shape memory alloy actuators directly pulling a load.

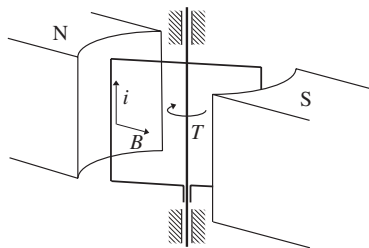


Figure 1.3 A DC motor as a geometrical transducer.

In most cases, the time lapse between the discovery of a new transducing material and its eventual application in the development of actuators might be decades or even centuries. This is the case, for instance, of ER and MR fluid actuators (see Chapter 6). The modification of the rheological behavior of both types of fluid in response to electric or magnetic fields, respectively, has been known since the late 1940s. Only recently have they been applied industrially in the context of vibration isolation (see Case Study 6.3, page 240).

1.2.1 Energy domains and transduction phenomena

Most often when dealing with transducers, seven main energy domains are considered, namely, chemical, electrical, magnetic, mechanical, optical, fluid and thermal. Transduction can be found between any two of these energy domains. In addition, different transduction phenomena are possible for a given pair of energy domains. Some of the transduction processes of interest when developing actuators are briefly analyzed in the following paragraphs.

1. *Thermomechanical transduction.* In this energy conversion process, the input energy is in the thermal domain and the output energy in the mechanical domain. Several actuators can be developed by following this conversion scheme:
 - (a) *Shape memory alloy (SMA) actuators.* In this type of actuators, the input thermal energy triggers a phase transition in the alloy, which results in the shape recovery of a previously deformed state. These actuators are discussed in detail in Chapter 3.
 - (b) *Thermal actuators.* In this type of actuators, the different thermal expansion coefficients of two thin metallic laminas cause a bending of the composite structure upon heating and cooling. These actuators are described in more detail in Section 1.10.2.
 - (c) *Thermally active polymer gels.* Some polymer gel actuators respond to thermal stimuli. These are reviewed in more detail in Chapter 4.
 - (d) *Thermal expansion actuators.* It is well-known that temperature changes cause expansion–contraction of all materials. Thermal expansion can be considered a direct thermomechanical transduction process.
2. *Magnetomechanical transduction.* These actuators establish an energy flow from the magnetic domain to the mechanical domain and vice versa. Again, several actuators can be developed, depending on various different transduction phenomena:
 - (a) *Magnetostrictive actuators.* Magnetostrictive actuators exhibit a reorientation of magnetic dipoles in the presence of an externally imposed

magnetic field. Magnetic domain reorientation results in extension-contraction in the dominant direction. These actuators are analyzed in Chapter 5.

- (b) *Magnetorheological fluid (MRF) actuators.* MRFs exhibit changes in their rheological properties when subjected to external magnetic fields. The apparent viscosity of these materials is thus modified according to the magnetic field. They are semiactive actuators: that is, they can only dissipate energy. MRF actuators are discussed in Chapter 6.
 - (c) *Magnetic shape memory alloy (MSMA) actuators.* In most instances, MSMA are considered a subclass of magnetostrictive actuators. However, they exhibit very different actuator characteristics and are evolving into an independent new class of actuators. They are addressed in Chapter 1.
3. *Electromechanical transduction.* The energy in the input electrical domain is transformed into mechanical energy. In most of the following actuator technologies, the transduction process is reversible. Some of the technologies listed below are used concomitantly with the converse transduction process in what are known as smart actuators (see Section 1.3).
- (a) *Electromagnetic actuators.* The Lorentz interaction between a flowing electrical charge and a magnetic field is exploited to supply either translational or rotational mechanical energy to the coil. The magnetic field can be established either by means of permanent magnets or by a second coil. This is a well-known, traditional actuator technology, and in this book, it is only mentioned as a reference for comparison with emerging technologies.
 - (b) *Piezoelectric actuators.* The converse piezoelectric effect resulting from the interaction of an imposed electric field and electrical dipoles in a material results in a deformation. This deformation is used to drive the plant. The converse piezoelectric effect can be used directly or through geometrical transducer concepts. This is analyzed in detail in Chapter 2.
 - (c) *Shape memory alloy (SMA) actuators.* These actuators have already been mentioned in connection with thermomechanical transduction. Thermal energy is usually supplied through resistive heating (Joule effect), and, hence, these can also be considered electromechanical transducers.

In the context of smart actuators, a linear relationship between the electrical resistance and the displacement is used to establish a sensor model.
 - (d) *Electroactive polymer (EAP) actuators.* Within the broad family of EAP actuators, dry type polymers directly exploit Maxwell forces or the

electrostrictive phenomenon to obtain mechanical energy from electrical input energy. In addition, some ionic EAPs (also referred to as wet EAPs) are triggered by small electric fields. All these actuators are presented in Chapter 4.

- (e) *Electrorheological fluid (ERF) actuators*. Like MRF actuators, the rheological properties of ERF actuators are altered when an electric field is applied. Again, these are semiactive actuators and so can only dissipate the energy of the plant. They are analyzed in Chapter 6.

4. *Fluid-mechanical transduction*. Some traditional actuators (pneumatic and hydraulic actuators) convert the pressure of a fluid into mechanical energy, either rotational or translational.

1.2.2 Transducer basics

A transducer is a two-port device. Unless it is intended to transduce between different types of energy within the same domain, it will have four terminals.

As noted earlier, two conjugate variables (effort, v , and flow, f) at each port will define the power entering and leaving the transducer. A general scheme of this two-port device is shown in Figure 1.4.

For a linear transducer, the relationship between effort and flow at both terminals will have the following form:

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix} \quad (1.1)$$

According to the structure of the two-dimensional matrix defining a particular transducer, these can be classified into the following:

- *Transforming Transducers*. In a transforming transducer, the following relationships between coefficients in the transducer matrix are met:

$$t_{12} = t_{21} = 0 \quad \text{and} \quad t_{22} = -\frac{1}{t_{11}} \quad (1.2)$$

From the relationships of Equation 1.2, it follows that the flow in port 1, v_1 , is linearly related to the flow in port 2, v_2 , k being the constant of

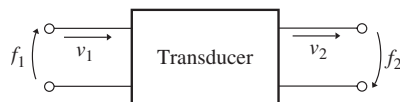


Figure 1.4 Two-port transducer: input power defined by conjugate variables f_1 and v_1 and output port power defined by variables f_2 and v_2 .

proportionality. Likewise, the effort in port 1 is related to the effort in port 2 by a constant, which is the negative reciprocal of k :

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} k & 0 \\ 0 & -1/k \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix} \tag{1.3}$$

- *Gyrating Transducers.* In the case of gyrating transducers, the following relations apply:

$$t_{11} = t_{22} = 0 \quad \text{and} \quad t_{21} = -\frac{1}{t_{12}} \tag{1.4}$$

In gyrating transducers, the flow in port 1 is linearly related to the effort in port 2 by a constant, g . Likewise, the effort in port 1 is linearly related to the flow in port 2, the constant of proportionality being the negative reciprocal of g . The following relationship between input and output conjugate variables is found in gyrating transducers:

$$\begin{bmatrix} v_1 \\ f_1 \end{bmatrix} = \begin{bmatrix} 0 & g \\ -1/g & 0 \end{bmatrix} \begin{bmatrix} v_2 \\ f_2 \end{bmatrix} \tag{1.5}$$

Equations 1.3 and 1.5 impose a causality condition between the conjugate variables of input and output ports. In particular, for the transforming transducer they indicate that only one of the flow variables v_1 or v_2 can be chosen as independent variables. Once a flow is specified as an independent variable, the flow in the other port follows from the causal relation of Equation 1.3. The same can be said for the efforts: that is, they are causally determined by Equation 1.3:

$$v_1 = k \cdot v_2 \tag{1.6}$$

$$f_1 = -1/k \cdot f_2 \tag{1.7}$$

For gyrating transducers, the causality relations of Equation 1.5 impose conditions between flow and effort in both ports. If a flow is chosen as an independent variable, the effort at the other port is causally determined:

$$v_1 = g \cdot f_2 \tag{1.8}$$

$$f_1 = -1/g \cdot v_2 \tag{1.9}$$

The results of transforming and gyrating transducers can be exploited to develop concomitant sensing and actuation in some instances. This is explained in more detail in the next section.

Different conjugate variables are defined according to the particular input and output energy domains of a particular transducer. The flow and effort corresponding to the most common energy domains are summarized in Table 1.1. Note that the definition of conjugate variables as those defining the power at each port does not apply to the case of the thermal energy domain.

Table 1.1 Conjugate variables in transducer ports for various energy domains.

Energy domain	Flow, v	Effort, f
Electrical	Current, i	Voltage, V
Fluid	Volume flow rate, Q	Pressure drop, P
Magnetic	Magnetic flux, Φ	Magnetomotive force, \mathcal{F}
Mechanical translational	Velocity, v	Force, F
Mechanical rotational	Angular velocity, ω	Torque, T
Thermal	Heat flow, q	Temperature, T

A complementary method of analyzing actuators is by means of the electric-circuit analogy. In the electric-circuit analogy, ideal effort sources (voltage sources in the electrical terminal and force sources in the mechanical counterpart) are used to drive an electrical and a mechanical impedance, Z_e and Z_m respectively. The result is a current flowing in the electrical port, I , and a mechanical flow, that is, velocity, v , in the mechanical port.

In the electric-circuit analogy, both ports are coupled through a black box representing the transduction process (see Figure 1.5). Thus, in the electric-circuit analogy, the equations describing the relationship between flow and effort in both the electrical and the mechanical domain are

$$V = Z_e I + T_{em} v \tag{1.10}$$

$$F = T_{me} I + Z_m v \tag{1.11}$$

In Equation 1.10, V is the voltage applied to the electrical terminal to drive the actuator, Z_e is the so-called blocked electrical impedance of the actuator, I is the electrical current flowing, T_{em} is the transducing coefficient from the mechanical to the electrical domain, F is the force acting on the actuator’s mechanical port, T_{me} is the coefficient of transduction from the electrical to the mechanical domain, Z_m is the mechanical impedance and, finally, v is the velocity at the mechanical port.

The electrical driving-point impedance, Z_{ee} , is defined (Hunt (1982)) as the ratio of the applied voltage to the current drawn when all the electromotive terms in the transduction process are suppressed. The mathematical formulation for the

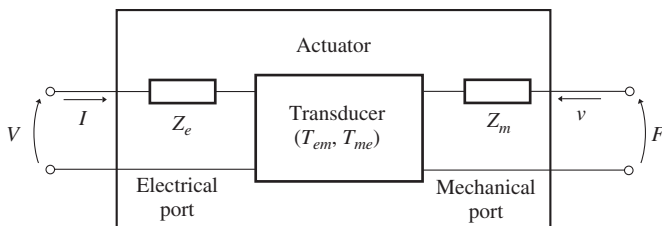


Figure 1.5 Electric-circuit representation of actuators.

driving-point electrical impedance is

$$Z_{ee} = \left(\frac{V}{I} \right)_{F=0} = Z_e + \frac{-T_{em}T_{me}}{Z_m} \quad (1.12)$$

The first term in the driving-point electrical impedance is the *blocked electrical impedance*, Z_e , which is defined as the electrical impedance of the actuator when the mechanical displacement is set to zero. The second term in the driving-point electrical impedance depends on three factors: the two transduction coefficients, T_{em} and T_{me} , and the mechanical impedance, Z_m .

The second term in the driving-point impedance is what is called the *motional impedance*, Z_{mot} . The fact that the motional impedance depends on the mechanical impedance, Z_m , indicates that even in the absence of external forces the actuator's electrical impedance will be affected by the motion of the mechanical port (Pratt (1993)). This dependence on the motion is, however, expected to be low where the actuator is driven at low frequencies.

The analysis of actuators in terms of the electric-circuit analogy is of particular interest for purposes of developing the *smart actuator* concept (see Section 1.5). In this context, a model of the actuator's blocked impedance can be used to estimate the position (or velocity) at the mechanical port, thus allowing the actuator to be used concomitantly as a sensor.

1.3 The role of the actuator in a control system: sensing, processing and acting

Motion control systems can be regarded as the paradigm in the application of actuators. In Systems Theory, the element whose motion is to be controlled is denoted as the *plant*. The ultimate objective of a motion control system is to drive the plant according to a desired reference *trajectory*.

Here, the term *trajectory* must be considered in the widest sense. As introduced in the previous section, the control system will only be capable of imposing one of the two conjugate variables defining the mechanical interaction with the plant at the actuator output port. Depending on how this interaction is established, the *trajectory* might be a collection of successive positions (flow) of the plant parameterized by the time. It could also be a reference force (effort) parameterized by time, and it may occasionally be some sort of relation (impedance) between the flow and the effort as a function of time.

In general, motion control systems drive the plant according to the reference trajectory by means of a combination of functions: sensing, processing and actuation. Some of these functions may not be present in a particular motion control system. This is true of the *feed-forward control* of a plant. In feed-forward control schemes, detailed and accurate models of the plant and the actuator are available so that it is possible to predict the driving signal needed to attain the reference trajectory. Sensors are therefore not strictly necessary.

The role of the different components in MCS is discussed in the following paragraphs:

1.3.1 Sensing

As noted previously, sensors are transducing devices that monitor the status of a parameter of the plant. In a general motion control scheme, the reference trajectory must be compared to the actual one. Reactive measures to counteract deviations can then be implemented on the basis of this comparison.

The use of sensors in *feedback control* motion systems provide means for improving the robustness of the whole process. Additionally, they enable the implementation of disturbance rejection strategies. Feed-forward control schemes (sensorless) are susceptible of being affected both by inaccuracy in the plant and actuator models and by external (to the plant and the actuator) and internal disturbances. On the contrary, feedback schemes are much more robust against disturbances and can make allowance for inaccuracy in the models.

Sensors monitor the status of the plant, ideally without influencing it. Since they are transducing devices, there will always be a flow of energy through them (a sensor in which no flow of energy is established in either direction is not physically practicable). Since they must operate without affecting the plant, the flow of energy must be minimized. Consequently, they are mostly low-power, miniaturized devices.

1.3.2 Processing

The processing function in a motion control system is done by the controller. The controller provides the equivalent to the intelligence in a control system. It usually receives the reference trajectory as an input (most likely from an upper-level task planner in a hierarchical control approach) and computes the required action to drive the plant according to the reference trajectory.

The controller in feedback schemes obtains information on the status of the plant through sensors. On the basis of this information, the deviation from the reference trajectory is calculated and corrective actions implemented. Corrective actions take the form of input energy in the domain of the actuator's input port.

The controller in feed-forward schemes computes the driving actions according to the reference trajectory and models establishing the relationship between control actions and plant trajectory. The controller in this scheme might receive sensor data but is not used in a reactive approach to counteract possible deviations from the reference trajectory.

In controlling the flow of energy to or from the plant, the controller modulates the input power to the actuator. Since the input power at the electrical port will be determined by both the flow (current) and the effort (voltage), one possible approach is to command the level of input current or voltage.

The choice of the input conjugated variable to be controlled has direct implications on the performance of the actuator and, hence, on the plant. A typical example

of this situation can be found in current- or voltage-controlled piezoelectric actuators (see Chapter 2). In piezoelectric actuators, voltage control produces hysteretic behavior, while current or charge control produces linearized plants.

In practice, electrical power supplies with variable voltage are not readily available. An alternative means of modulating the input power is to switch between discrete levels and produce averaged values. Moreover, in some instances, switching techniques are the only way to effectively drive an actuator (see Chapter 4). The rationale of using switching techniques is described in more detail in Section 1.4.

1.3.3 Actuation

In a motion control system, the actuation function is accomplished by the actuator. The actuator is the only unavoidable component of a motion control system. As previously defined, the actuator establishes a flow of energy between the electrical and the mechanical domains. The function of the actuator is to impose a state on the plant, ideally without being affected by the load.

The plant is driven according to the reference trajectory, by either increasing or decreasing the energy level of the plant. The particular way this energy flow is established is determined by the joint interaction of the plant and the actuator at the output port.

This can be easily illustrated by the simple example of an actuator driving a mass. The actuator can impose an effort (force) on the mass. However, the flow (velocity) of the plant will be determined by the inertial characteristics of the mass. Here, the mass (plant) is acting as an admittance (it receives an effort and determines the flow).

In most situations, the plant acts as an admittance. According to the *principle of causality* (Hogan (1985a)), *the action of the motion control system on the plant must be complementary to it*, that is, wherever the plant is an admittance, the control system behaves as an impedance (accepts a flow and imposes an effort).

The actuator ideally will not be affected by the load. In practice, the load will impose limits on the actuator's power delivery. Because of its dependence on the load, the actuator usually behaves as a low pass filter: that is, in the frequency domain, actuation is only possible up to some cutoff frequency, which is closely related to the device's mechanical time constant (see Figure 1.6). The dependence on the load can also be seen in the typical effort (force) versus flow (velocity) curves of all actuators. Figure 1.7a shows the torque–velocity curve for a permanent magnet DC electromagnetic motor, while Figure 1.7b shows the same curve for a Travelling Wave Rotational Ultrasonic Motor. The available torque is reduced as the actuation velocity is increased, while, ideally, this should be kept constant for all velocities. There is always an effort (stall torque) above which no flow (velocity) is available.

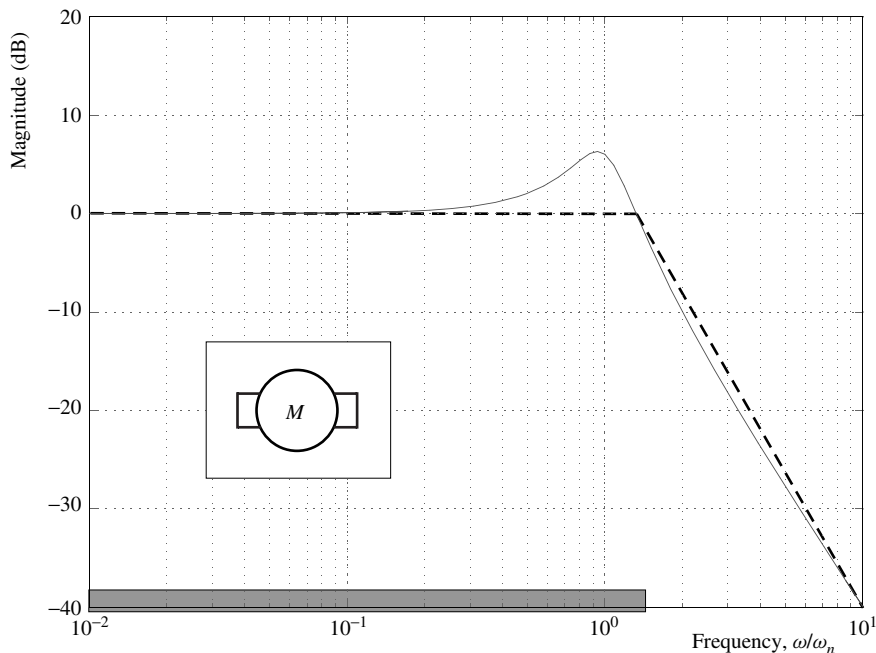


Figure 1.6 Limit in the frequency bandwidth of motors as a consequence of finite power: allowable frequency range highlighted in thick black.

1.3.4 Impedance matching

According to the discussion above, the entire motion control system can be seen as an intelligent modulation of energy flow between an electrical source and the plant, so that it is driven according to a reference trajectory. For this to be properly accomplished, energy flow must be smoothly established. Energy must flow from the electrical power source to the actuator through the input port, and then after being transduced, from the actuator output port to the plant.

Let us recall here the case of a vibrating string fixed at both ends (see Figure 1.8a). When the equilibrium state is altered by imposing a displacement on the string (playing the guitar), a wave is generated and it travels towards both ends (see Figure 1.8b). Since the mechanical impedance of the string and the frame (which holds the string at both ends) are dissimilar, the wave is reflected and a traveling wave in the opposite direction is established. The superposition of traveling waves in opposite directions leads to a standing wave that dissipates all the input energy through frictional mechanisms (see Figure 1.8c).

In this example, the input energy (the energy of the vibrating string) cannot be transferred to the frame (because of the impedance mismatch). The energy is reflected at the interface and is completely dissipated in the string.

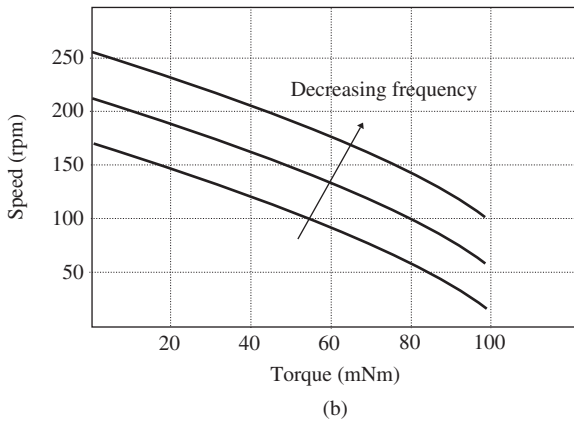
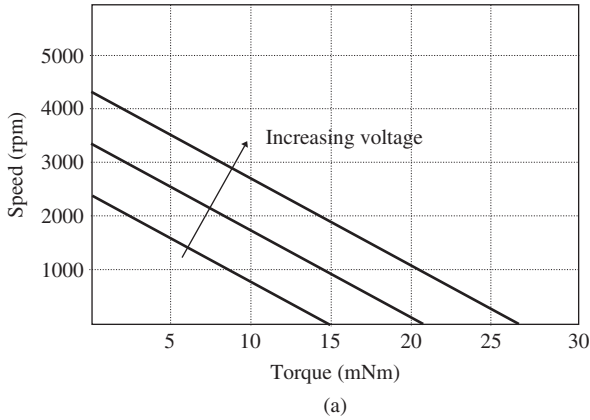


Figure 1.7 Effect of the load on the imposed velocity for (a) a permanent magnet DC motor and (b) an ultrasonic motor.

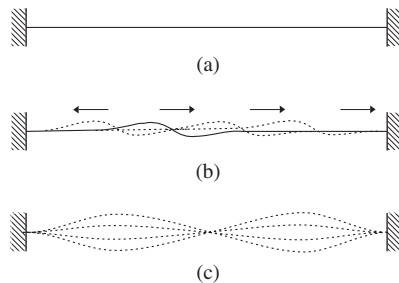


Figure 1.8 Effect of an impedance mismatch on power transmission: the perturbation of the equilibrium in a string (a), results in traveling waves towards the frame (b). Energy is reflected because of the impedance mismatch and dissipated in the string (c).

In controlling the energy flow in motion control systems, an analogy can be established with the previous example. In the mechanical port, the impedance of the plant (ratio of required velocity to force) will, in general, be different from the actuators' output impedance. If no means for matching these impedances is provided, the energy, rather than flowing, will be dissipated at the actuator.

This is exemplified by a permanent magnet DC electromagnetic motor driving a mass (plant) (see Figure 1.9). The typical operating range of DC motors is that of low torque and high velocity, that is, a high mechanical impedance. In general, the driving requirements of plants are low velocity and high torque, that is, low mechanical impedance. If no matching is provided, the DC motor will not be able to impart any motion to the mass, that is, the stall torque will be lower than the required driving torque. All the energy input is then dissipated to heat the motors' armature (see Figure 1.9a). After matching the mechanical impedance at the output port, energy flows and the DC motor can impart a movement to the mass (see Figure 1.9b).

There is a similar situation at the electrical input port. See Chapter 2 for a detailed description of electrical impedance matching when driving piezoelectric actuators in resonance.

Figure 1.10 represents the different constitutive parts of a motion control system for a smooth energy flow from the electrical power source to the plant. Note that

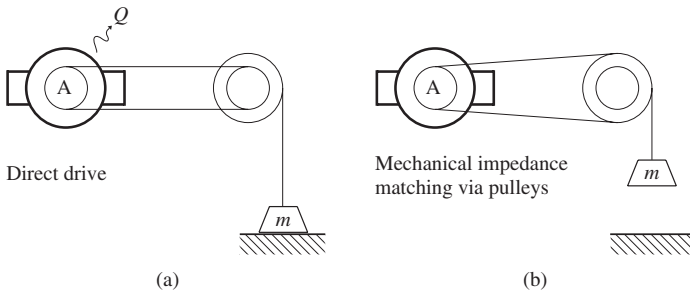


Figure 1.9 Mechanical impedance matching: (a) the actuator heats up as power is not transferred to the load and (b) the power can be transmitted to the load after pulley impedance matching.

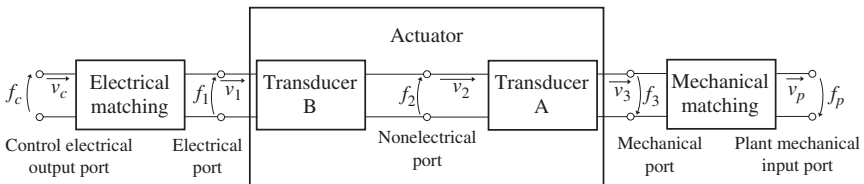


Figure 1.10 Schematic representation of electrical and mechanical impedance matching of an actuator.

the actuator will comprise any requisite subsystem with the function of electrically driving a possible nonelectrical input port transducer.

1.4 What is mechatronics? Principles and biomimesis

The term mechatronics was coined in Japan in the mid-1970s to denote the engineering discipline dealing with the study, analysis, design and implementation of hybrid systems comprising mechanical, electrical and control (intelligence) components or subsystems. Ever since, mechatronics has been understood to mean the integrated and concurrent approach of engineering disciplines for the study of such hybrid systems.

1.4.1 Principles

The black box convention for system analysis is used throughout this book. A system, then, is conceived as a black box with an input and an output port. Systems can interact with one another to set up systems with added complexity and functionality. A mechatronic system is thus a hybrid system including sensor subsystems, control subsystems and actuator subsystems.

Subsystems can be connected in a cascade configuration. In this configuration, there is always an interaction between the output port of one subsystem and the input port of the consecutive one. As discussed earlier, the state of the interaction between two cascaded systems is defined according to conjugated variables.

Mechatronic systems are in many instances synonymous of motion control systems. As such, they include different functional subsystems as introduced in Section 1.3. A very interesting feature of mechatronic systems is the *combination of functions in the same component*. Here, we are especially interested in the possible combination of sensing and actuation functions in a subsystem. This aspect is analyzed in more detail in Section 1.5, when dealing with concomitant sensing and actuation.

The combination of functions by means of mechatronic integration of disciplines in the design of actuators has clear functional benefits. The *miniaturization of systems* can be seen as a direct consequence of this combination of functions. Yet, the paradox of opposite rationales in the design of sensors and actuators must be addressed, see Section 1.5.

This book focuses particularly on analysis of the actuator subsystem within a mechatronic system. The actuator subsystem itself can be shown to exhibit the same mechatronic characteristics as a motion control system. This means that the actuator can be analyzed as a mechatronic system, and it will benefit from the intrinsic cross-fertilization between engineering disciplines (Reynaerts *et al.* (1998)).

The concept of an actuator as a true mechatronic system will be illustrated with the example of a resonant piezoelectric drive. A piezoelectric actuator is an electromechanical device in which the converse piezoelectric effect is used to transduce from electrical to mechanical energy domains (see Chapter 2).

A piezoelectric ceramic is characterized electrically by a capacitive load that is out of resonance and a resistive electrical load that is at resonance (local minimum in mechanical impedance) and antiresonance (local maximum in electrical impedance). Piezoelectric resonators are driven close to their resonance or antiresonance frequencies. In such a driving condition, the electrical load is resistive, and so input voltage and current will exhibit a phase lag close to zero.

In actuators of this type, an applied external load or temperature change will lead to a shift in the resonance frequency (see Figure 1.11). If this is not compensated for, the operating point of the piezoelectric drive will generally not be perfectly tuned. Note the relative position of the original operating point (light grey dot at f_1 in Figure 1.11) with respect to the resonance as compared to the new relative position (grey dot at f_1).

With a mechatronic approach, a self-tuning electrical driver can be designed, which will track any possible fluctuation in the resonance characteristics of the actuator, and, thus, the new operating point will be tuned to the new resonance curve (see grey dot at f_2 in Figure 1.11). In so doing, the phase between voltage and current can be used as an indicator of the electrical impedance of the actuator. This can then be used to close the loop, for instance, by means of a phase locked loop (PLL).

The resonant piezoelectric actuator as described above includes an actuator system (the voltage-driven piezoelectric resonator), a sensor system (monitoring

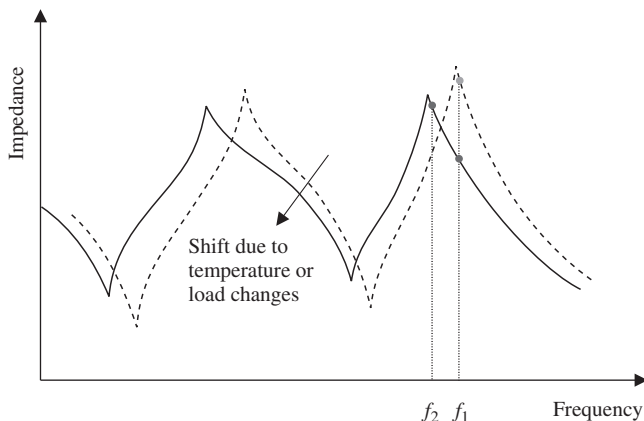


Figure 1.11 Effect of temperature or load fluctuations on the resonance characteristics of piezoelectric actuators and corresponding modification of the operating point.

the phase lag or impedance condition at the input port) and a disturbance rejection control system (the PLL drive).

1.4.2 Mechatronics and biomimesis

Engineering disciplines have always looked to nature as a source of inspiration. Several million years of evolution have seen living creatures progress to their current state. Engineering has very often taken nature as a model and has mimicked biological structures. By way of example, Figure 1.12 shows a biological structure usually taken as a model in the development of helicopter blades and airplane wings.

Mechatronics as an engineering discipline may also benefit from seeking a source of inspiration in nature. As noted earlier, mechatronic systems are in most cases equivalent to motion control systems. As such, the motor control structure of upper mammals is a perfect model in which to find inspiration.

Hierarchical motor control in mammals as a model

Hierarchical control schemes are common in motion control systems. There is sufficient evidence to support the view that the structure of the motor control system in mammals is hierarchically organized. This follows from the excellent performance of both human and nonhuman primates in manipulation tasks. This performance in manipulation comprises, among other functions, superb response to disturbance, for example, increased prehensile force following slippage of grasped objects, and perfect modulation of upper limb (impedance controlled) interaction with the environment.

In these particular manipulative tasks, feedback control schemes involving structures in the central nervous system (CNS) do not seem feasible. In fact, the shortest loop delay involving neural transmission from skin receptors to the CNS and back is in the region of 100–150 ms. If these feedback loops involve computing at the brain level (for instance, in visual feedback operations) the loop delay can reach up to 200–250 ms. With loop delays of this magnitude, the effectiveness

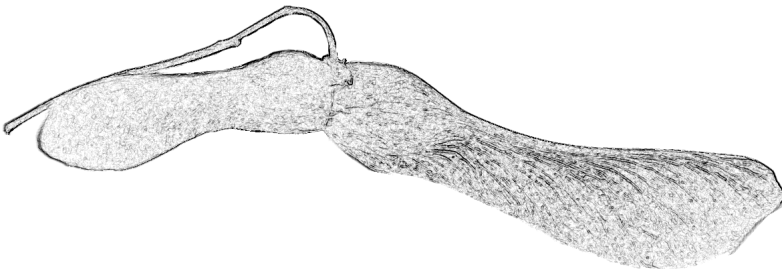


Figure 1.12 Biological model of helicopter blades.

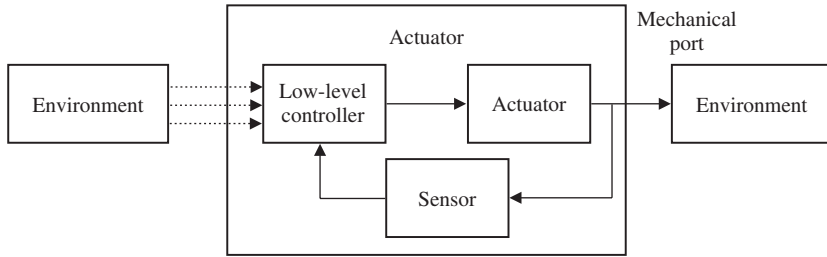


Figure 1.13 Hierarchical representation of the human motor control system.

of feedback modulation of impedance or the response to disturbance would be very much compromised.

Hierarchical control schemes mimicking the structure of the human motor control system are a common approach. Figure 1.13 shows a schematic representation of such a hierarchical control scheme. An upper-level task planner is in charge of sending motion commands (reference trajectories) to low-level controllers. The low-level controllers interact with the plant through sensors and actuators (including the corresponding impedance-matching stages). As seen from the upper-level controller, the process is an open loop.

Switching control of muscle contraction as a model to modulate the input power in actuators

The human musculoskeletal system is driven through switched techniques. Motor stimuli reach the various different muscles through motoneurons. Each muscular stimulus leads in the first instance to muscle contraction followed by relaxation. The time constants of the contraction and relaxation processes are very different. The muscle contraction time constant is much lower than the relaxation time constant; as a result, the musculoskeletal system responses during contraction and relaxation exhibit different dynamics (see the different dynamics in a muscle twitch inset in Figure 1.14).

If repeated stimuli reach the muscle prior to total relaxation, summation occurs, and the result is increasing contraction. Overall muscle contraction is a combination of increased contraction of individual fibers due to summation and increased recruiting of additional motoneurons, and, consequently, muscle fibers. See Figure 1.14 for a schematic representation of the switched control of muscle contraction.

In addition to position control of the human musculoskeletal system, there is sufficient evidence to believe that the modulation of the motor activity in antagonistic muscles is one of the mechanisms that mammals use to modulate the impedance around an equilibrium position (Hogan (1985b)).

Switching techniques as an approach to modulation of the flow of energy in actuators is of particular interest when actuators exhibit different dynamics in both directions (like in the case of muscle contraction–relaxation). This is generally true

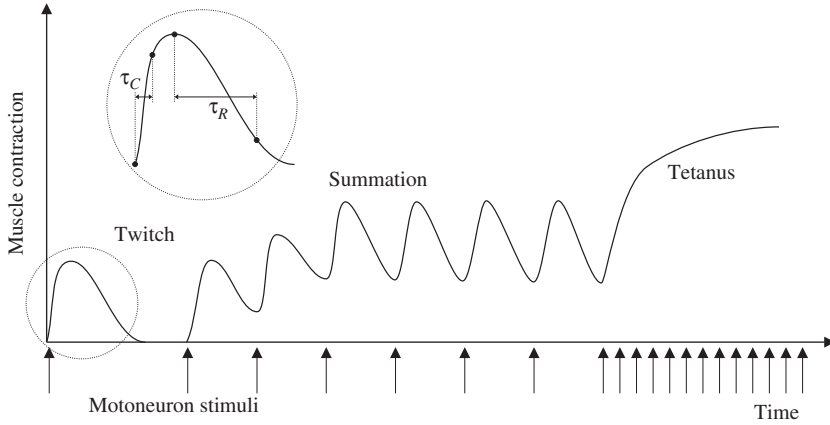


Figure 1.14 Biological model-switching techniques to modulate the flow of energy in actuators.

of thermal actuators, and, in particular, of SMA actuators. In these systems, the time constant for the heating process is generally much lower than for the cooling process (which is limited by thermal inertia and heat dissipation).

Wherever a discontinuity occurs in the change in length of an actuator (see Chapter 4), switching techniques may be the only possible solution for accurate positioning tasks. The discontinuity, as depicted in Figure 1.15, leads to mechanical states that are not attainable in equilibrium. In such a case, switching techniques can maintain the mechanical state without equilibrium within the margin of mechanical state error allowed by the application (Mitwalli (1998)).

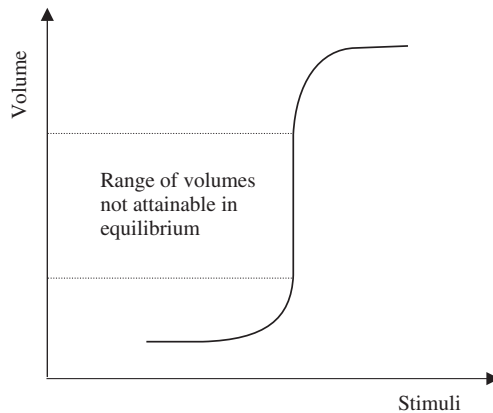


Figure 1.15 Discontinuity in volume–phase transformations leading to nonattainable mechanical states.

Actuation modes based on biological models

The previous two examples of biomimesis are more closely related to the way actuators can be driven and how the energy flow is modulated. Nature is full of models for establishing actuation principles. Here, we will briefly describe two locomotion models that inspired the development of the so-called *inchworm actuators* and *travelling wave linear and rotational ultrasonic motors* (see Chapter 2).

The first model is the locomotion process of some earth worms as depicted in Figure 1.16. This locomotion process is split into two cycles, in one of which the rear and front legs of the worm are fixed alternately to the terrain. In the second cycle, the intermediate segments of the worm elongate and contract alternately. Both cycles are nested to provide the locomotion.

The same principle is followed in the development of inchworm piezoelectric motors (see Section 2.4.3). Here, three independent piezoelectric ceramics are used to mimic the operation of rear and front legs (ceramics 1 and 3), and the intermediate segments (ceramic 2). The piezoelectric actuators 1 and 3 are driven according to the first cycle so that they clamp the rotor (displacer) alternately. The piezoelectric actuator 2 is driven according to the second cycle, mimicking the elongation and contraction of the intermediate segments of the worm.

The second locomotion principle is found in some millipedes and centipedes (see Figure 1.17a). The motion of the different legs is coordinated to produce an approximate sinusoidal pattern in both the elevation and the forward–backward movement. These sinusoidal movements in perpendicular directions produce an elliptic movement of each leg. This elliptic movement (which is implemented in successive legs with a small delay) provides incremental traction to the millipede.

The same principle is exploited in travelling wave ultrasonic motors. The case of linear piezoelectric motors based on this principle is described in Section 2.3.3, while the case of rotational drives is described in Section 2.3.2. In both the approaches, a laminate structure composed of an elastic substrate and a piezoelectric ceramic is driven in resonance to produce (through superposition of sinusoidal perpendicular

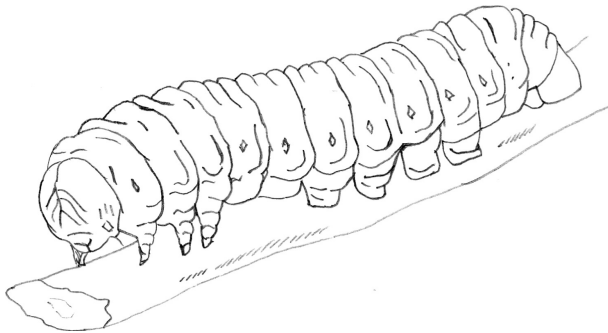


Figure 1.16 Biological model for inchworm piezoelectric actuators.

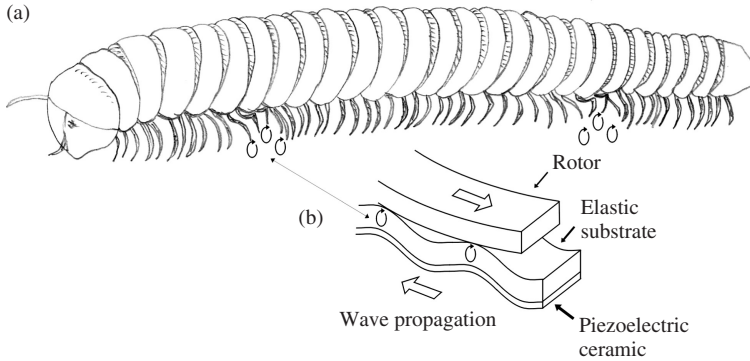


Figure 1.17 Biological model for travelling wave ultrasonic linear and rotational motors.

motions) an effective elliptic displacement at the interface between rotor and stator (see Figure 1.17b). This provides traction through a frictional transmission.

1.5 Concomitant actuation and sensing: smart structures

In previous sections, we discussed how transducing devices can be configured either as sensors or as actuators. Here, we stress the fact that transducers can implement both crucial roles – sensing and actuation – in a motion control system. The former provides a tool for monitoring the status of a system and the latter enables us to impose a condition on a system.

In some special cases, transducers can be used both as sensors and as actuators. Take for instance, DC electromagnetic motors. Rotational electromagnetic motors can function both as actuators (i.e. rotational mechanical energy is produced by the application of a driving voltage), and as generators (i.e. the rotation of the output shaft produces a voltage, proportional to the rotation rate, at the electrical terminals).

Let us consider the case of a permanent magnet DC electromagnetic motor. DC electromagnetic actuators make use of Lorentz's electromagnetic interaction between a permanent magnetic flux, B , and an electrical current, i , flowing in a coil (see Figure 1.3). In an appropriate configuration, if the coil is allowed to rotate, the magnetic interaction produces a torque, T , on the coil, causing rotation. The torque developed by the electromagnetic interaction can be expressed as:

$$T = k_T i \quad (1.13)$$

where k_T is the so-called torque constant of the DC motor.

Similarly, since the DC motor coil is rotating in a magnetic field, induction will take place and a (back) electromagnetic voltage (EMF) will be induced. The

expression for the back EMF is:

$$V_{EMB} = k_V \omega \quad (1.14)$$

where ω is the angular rate of the coil and k_V is the voltage constant or back-EMF constant of the motor.

When the DC electromagnetic motor is driven by an input voltage, an angular rate will be developed. It can be demonstrated, in a first approximation, that the angular velocity of the motor obeys the following differential equation when no external load is applied to the shaft:

$$\frac{d\omega}{dt} = -\frac{1}{J}k_F\omega(t) + \frac{1}{J}k_M i(t) \quad (1.15)$$

where J is the motor's rotational inertia and, k_F is the viscous damping constant equivalent to the frictional forces in the motor.

Likewise, when no voltage is applied to the DC motor terminals and the shaft is rotated at a constant velocity, ω , a voltage will be developed between the terminals according to Equation 1.14. This means that the motor works either as an actuator or as a sensor.

A transducer cannot be operated both as a sensor and as an actuator simultaneously unless a model of the transduction is available; in other words, the device can only be used for one of its functions at a time. For practical purposes, this means, in the case of the previous example, that if a rotational velocity is being imposed by means of a DC electromagnetic motor, the same motor cannot be used to sense the rotational velocity that is being imposed.

The previous discussion is true and holds for all transducers; however, some sensing and actuation functions can still be implemented concomitantly. Equations 1.13 and 1.14 can be rewritten according to the following expression:

$$\begin{bmatrix} V \\ i \end{bmatrix} = \begin{bmatrix} 0 & k_V \\ k_T & 0 \end{bmatrix} \begin{bmatrix} T \\ \omega \end{bmatrix} \quad (1.16)$$

It can be shown that $k_V = -1/k_T$; thus, the motor can be classified as a gyrating transducer. As discussed previously, in gyrating transducers, there is a causal relationship between the effort at one port and the flow at the other port. If the torque (effort) is selected as the independent variable, the current (flow) is causally determined. The motor can be used to sense the load (torque) by monitoring the electrical current.

Piezoelectric actuators are a similar case. A piezoelectric actuator establishes a flow of energy from the electrical to the mechanical domain according to the constitutive equations of the piezoelectric effect (see Chapter 2). When no external load is applied to a piezoelectric stack actuator, the displacement (strain) will be a nonlinear, hysteretic function, $S_1(V)$, of the voltage applied at the input port. Wherever an external force is applied to the actuator, it will act as a disturbance to the output displacement. The complete relationship between strain, voltage and

load will take the form of Equation 1.17 and is commonly called an operator-based actuator model of the piezoelectric stack transducer (Kuhnen and Janocha (1998)).

$$S(t) = S_1(V) + kf(t) \quad (1.17)$$

where k is the piezoelectric stack stiffness.

Similarly, the charge developed in the piezoelectric stack, $Q(t)$, will be a direct function of the load applied to the transducer, $f(t)$. This time, the voltage-induced charge during operation will act as a disturbance to the operator-based sensor model described by Equation 1.18.

$$Q(t) = df(t) + Q_1(V) \quad (1.18)$$

where d is the piezoelectric coefficient and $Q_1(V)$ is a nonlinear, hysteretic function of the voltage.

Again, even though the piezoelectric stack cannot be used to impose a displacement (strain) and to concomitantly sense it, the sensor model of Equation 1.18 can be used to estimate the load on the actuator, that is, the piezoelectric stack is being used concomitantly to impose a displacement and to sense the load. The estimated load can then be used to compensate for its disturbing effect on the displacement of Equation 1.17 (Kuhnen and Janocha (1998)).

A model of the transduction process can be used to implement both functions (sensing and actuation) at a time. Before discussing this possibility in detail, let us recall here Equation 1.10, which describes the relationship between effort and flow variables in the electric-circuit analogy:

$$V = Z_e I + T_{em} v \quad \text{and} \quad F = T_{me} I + Z_m v$$

The first equation describes the transducer as an actuator, that is, the application of a voltage, V , leads to a current drawn, I , and to an output velocity, v . The Laplace transform of this first equation is:

$$V(j\omega) = Z_e I(j\omega) + T_{em} U(j\omega) \quad (1.19)$$

The overall electrical voltage includes a term dependent on the current drawn, $Z_e I(j\omega)$, and a term related to the output velocity, $T_{em} U(j\omega)$. This equation indicates that the output velocity could be estimated by measuring the overall voltage, V , and subtracting the voltage drop, V_{Z_e} , across the actuator's blocked impedance, $V_{Z_e} = Z_e I(j\omega)$.

The above result provides the basis for estimation of the actuator's motion from a *bridge circuit configuration*, as shown in Figure 1.18. This result is important in that it could lead to: (i) modification of the actuator's behavior (for instance its damping characteristics) through the implementation of feedback control loops based on the estimation of the velocity and (ii) collocated and concomitant sensing and actuation.

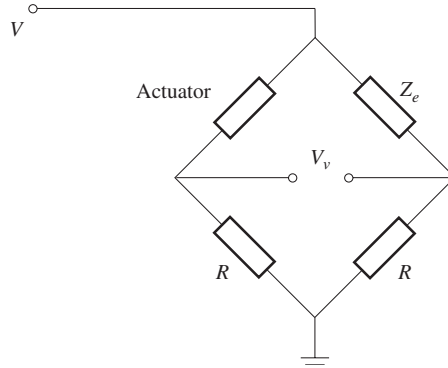


Figure 1.18 Bridge circuit for producing a signal proportional to the actuator's velocity in concomitant sensing and actuation.

If a copy of the actuator's blocked impedance is used in the bridge circuit branch as depicted in Figure 1.18, the voltage across the bridge, V_v , is proportional to the actuator's velocity.

The first approach, that is, modification of the actuator's damping properties, has been studied in the context of voice coil loudspeakers (de Boer (1961)). In this case, the feedback from the unbalanced bridge voltage is utilized to increase damping around the resonance frequencies. The second approach has been implemented in collocated and concomitant position and velocity feedback in piezoelectric actuators (see Dosch *et al.* (1992) and Hagwood and Anderson (1991)).

The main problem in this approach is measurement of the actuator's blocked impedance. It has been found that in most implementations the blocked impedance, rather than being constant and independent of the actuator's motion, is a nonlinear function of the current drawn.

Ideally, if output velocity could be estimated from the voltage across the bridge, the sensing part of the electric-circuit analogy (see Equation 1.20) could then be used to produce an estimate of the mechanical conjugate variable (the force).

$$F(j\omega) = T_{me}I(j\omega) + Z_mU(j\omega) \quad (1.20)$$

In some instances, two-directional transduction of the same conjugated variable can be achieved when a transducing material is used to develop an actuator. This is only possible where the actuation process is accompanied by a concomitant change in any of the material properties of the transducer.

This is true of shape memory alloy actuators (SMAs) (see Chapter 3). In SMAs, thermal input energy is used to promote a phase change in the material. This phase change is accompanied by recovery of the shape induced by deformation. A number of physical properties of the material are altered during the process of shape recovery. In particular, the electrical resistivity of the material is modified by the thermally driven shape change. The electrical resistance can be used to monitor

the shape recovery. The actuator can be used to impose a displacement (strain) and simultaneously to sense this displacement.

Concomitant sensing and actuation is a very powerful phenomenon in mechatronic system design (see Section 1.4). As shown above, it allows functions to be shared on a single component. When properly exploited, this can result in very compact and smart solutions.

On the basis of the use of concomitant sensing and actuation is the concept of a *smart actuator*. When a two-directional transducer of this type is embedded in a structure, the combination is usually referred to as a *smart structure*.

The term *active structures* is also commonly found in the literature. The main difference between a smart and an active structure is more a matter of the degree of integration than of the functionality of the embedded smart actuators. In smart structures, a higher degree of integration is assumed: that is, two-directional transducers are highly integrated in the structure so that the whole structure can be considered a functional continuum.

In smart actuators, two functions are combined on a single component. When analyzing smart actuators, particular attention must be paid to the rationale behind the development of monitoring transducers (sensors) and acting transducers (actuators).

As noted earlier, sensors are intrinsically low-power transducers. A minimum energy interaction with the plant must be ensured so that the monitoring process does not interfere with the plant. Miniaturization is therefore a logical and desirable trend.

On the other hand, actuators are intrinsically high-power transducers and as such should impose a state without being disturbed by the plant. In actuators, the trend toward miniaturization is not a logical consequence of their interaction with the plant.

There are two opposite design goals driving the development of sensors and actuators. The former are low-power devices, best approached in a miniaturized fashion, while the latter are intrinsically high-power devices, conceptually the opposite of miniaturized components. These apparently opposing requirements can only be met by high-power density transducing materials. *Power density* in emerging actuators is considered throughout this book as one of the driving forces in the development of new technologies.

1.6 Figures of merit of actuator technologies

Actuators drive plants in motion control systems in obedience to control inputs. They are used to impose the controlled variable on the plant in accordance with the reference trajectory.

Imposing a state on the parameter of the plant raises a number of issues:

1. *Univocal correspondence between input signal and imposed system variable.* Ideally, there should be a unique output value corresponding to the system's parameter.

2. *Linearity.* Even though the above univocal correspondence will not generally be linear, linearity is always desirable.
3. *Stability.* The correspondence between input and output should not be influenced by drifts. The intrinsic high-power characteristics of actuators usually leads to thermal drift.

In selecting actuators for a particular application, a number of requirements may arise. These include power or force density, efficiency, size and weight, and cost. The following paragraphs briefly describe the figures of merit of actuators. In some instances, these figures of merit are perfectly quantifiable (e.g. force or power density); in other cases, quantification is not possible, and a thorough analysis of the application and the actuator characteristics for matching will be required.

The different figures of merit are arranged in the following categories: dynamic performance, behavior upon scaling, static performance, impact of environmental parameters, suitability to the application and cost.

1.6.1 Dynamic performance

In general, actuators are used under dynamic operation conditions. Dynamic operation entails continuous changes in the reference trajectory and in the loading conditions imposed by the mechanical interaction with the environment at the output port.

Dynamic operation usually produces changing conditions in the amount of energy flow across the actuator (power requirements), in the relative value of the conjugate variables (velocity and force) at the mechanical port and in the efficiency of transduction between input and output energy.

There are several indicators that can be used to measure the dynamic performance of actuators. Some of these are analyzed in the coming sections.

Power density and specific power density

Power density, P_V , is the ratio of the maximum available mechanical output power, P_{out} , to the volume of the actuator, V :

$$P_V = \frac{P_{out}}{V} \quad (1.21)$$

If the ratio of output mechanical power to the weight, ρV , of the actuator is considered, this defines *specific power density*, P_ρ :

$$P_\rho = \frac{P_{out}}{\rho V} \quad (1.22)$$

Power density and specific power density are measures of the rate of energy delivery at the mechanical port. They are also a measure of how suitable a transducing technology is as a smart actuator that is also for simultaneous use as a sensor.

Work density and specific work density per cycle

Like power density, *Work Density per cycle*, W_V , is defined as the amount of mechanical work that an actuator can deliver during an actuation cycle and is defined by the ratio of output work to volume:

$$W_V = \frac{W_{out}}{V} \tag{1.23}$$

Likewise, *specific work density per cycle*, W_ρ , is defined as the ratio of maximum available output mechanical work per actuation cycle to the weight of the actuator:

$$W_\rho = \frac{W_{out}}{\rho V} \tag{1.24}$$

In practice, both power and work densities are difficult to standardize as indicators for dynamic performance. This is basically due to uncertainty as to what should be considered the actuator volume or weight. Taking for example the case of traditional pneumatic linear actuators, if the volume or weight of the pneumatic cylinder is considered, the resulting work density is high as compared, for instance, to electromagnetic drives. However, if the accompanying components (power source, proportional or “on–off” valves, fluid-filtering components) are considered, the situation may be the reverse.

Power and work per cycle density and specific density are related through the actuator’s available working frequency, f . Thus,

$$P_V = W_V f \tag{1.25}$$

$$P_\rho = W_\rho f \tag{1.26}$$

Time constant and frequency bandwidth

The *Time constant*, τ , of a first-order system is the time taken for the output parameter of the system to reach 63.2% of its final value upon the application of a step input. In actuator systems, the mechanical time constant, τ_m , is usually defined as the time required for the output velocity of the actuator to reach 63.2% of its final value under no external load.

Owing to the inherent power limitations of any actuator system, the frequency response of the actuator will take the form of a low pass filter. This was illustrated in Figure 1.6. The cutoff frequency is defined as the frequency at which a decay of 3 dB in the output velocity of the actuator is observed.

The available bandwidth of the actuator is then defined by the cutoff frequency. Both the time constant and the maximum available frequency of an actuator are related by the following expression:

$$f = \frac{1}{2\pi \tau} \tag{1.27}$$

Energetic efficiency

The *efficiency*, η , in the transduction process in an actuator is defined as the ratio of the output mechanical energy, W_m , to the input electrical energy, W_e . In most emerging actuators, an extension of the actuator concept will be necessary in order to apply this definition, as the input of the transducer usually is in a nonelectrical domain: for example, magnetostrictive (magnetic domain), SMA (thermal domain), polymer gels (chemical domain).

$$\eta = \frac{W_m}{W_e} \quad (1.28)$$

Ideally, actuators are lossless devices, and, thus, efficiency in an ideal situation should be close to 100%. In practice, various different dissipative phenomena take place in the transducer or accompanying components, producing lower efficiency.

The transduction efficiency of all actuator technologies is a dynamic parameter. In general, the efficiency of the actuator is a function of the actuation conditions. The maximum efficiency is usually taken as the figure of merit.

1.6.2 Actuator behavior upon scaling

Current technological trends towards miniaturization impose strict requirements on actuators. Actuators are intrinsically high-power devices. The higher the power they can deliver, the more optimal their performance is.

Higher-power availability is an indication for instance of higher-frequency bandwidth or higher rejection of load disturbances. Miniaturization does not therefore logically lead to optimization of actuator performance. Rather, miniaturization of actuators must be seen as an application requirement.

The behavior of an actuator upon scaling is a characteristic of each technology and can be assessed by analyzing how the various different performance parameters (efficiency, power and work density, response time, force and stroke) evolve upon scaling.

The analysis of scaling of actuators is a complex task. The reader is referred to Madou (1997) and Peirs (2001) for a detailed study of scaling. Here, we will only give some theoretical background with experimental examples where possible.

For direct transducing operations, finding the available force, stroke and work density upon scaling is straightforward. If we let L be the dominant dimension of the actuator, the following can be said:

- *Force upon scaling.* When analyzing the available force of an actuator, the relevant dimension, L , for most technologies (e.g. piezoelectric actuators, shape memory alloy actuators, magnetostrictive actuators and most electroactive actuators) is the dimension of the cross section. The force, F , is then easily found following the scaling law of Equation 1.29.

$$F \propto L^2 \quad (1.29)$$

Upon scaling the dominant dimension, L , the available force scales as L^2 . Dimensions multiplied by 10 lead to available force multiplied by 100. The opposite occurs when scaling down the actuator's dimensions.

- *Stroke upon scaling.* In this case, the stroke, S , of the actuator is usually given as a percentage of its length. Thus, the dominant dimension is the length of the actuator, L . The stroke scales linearly with the scaling of the actuator:

$$S \propto L \quad (1.30)$$

When the dimensions of the actuator are multiplied or divided by 10, so is the stroke.

- *Work density and specific work density upon scaling.* Work can be readily determined as the product of displacement and force, $W_m = F \cdot S$. In addition, the volume of an actuator obeys a scaling law proportional to the third power of the dominant dimension, $V \propto L^3$. It follows, then, that the work density, defined as the ratio of work to volume, scales according to the following expression:

$$W_V \propto L^0 \quad (1.31)$$

The above equation indicates that for most actuator technologies, the available work density per cycle remains roughly constant upon scaling.

When considering the effect of scaling on dynamic properties (power density, time constant, frequency), the analysis becomes more complex. This entails identifying what particular factors will become dominant upon scaling, so that they effectively limit the dynamic performance of the actuator. Once the dominant factor is identified, its evolution upon scaling is estimated.

In particular, the time constant of the actuator (which can be used to work out all the other dynamic properties from the static ones) may be limited by a variety of factors for a single actuator technology. In the case of piezoelectric actuators in particular, the time constant (maximum frequency) can be limited by:

1. The resonance frequency of the actuator, which in most cases imposes the driving bandwidth,
2. The heating of the piezoelectric ceramic, which can lead to depolarization if the Curie temperature is reached,
3. The charging time of the capacitor.

In other actuator technologies, the limiting factors for the time response may be very different: heat dissipation (conduction or convection) in thermal actuators; mass transport or diffusion in ionic-type EAPs.

1.6.3 Suitability for the application

The suitability of an actuator technology for a particular application is hard to quantify, but it is usually one of the aspects considered when adopting a particular technology for an application. Suitability may involve a variety of aspects, but it commonly depends on a particular actuation characteristic that is intrinsically matched by the conditions of the application.

Two examples will illustrate this point. Let us first consider the temperature control in a process for mixing two fluids. The resulting fluid must remain between upper and lower temperatures of T_u and T_l respectively. In these conditions, a thermal actuator may be the right choice.

If, for example, an SMA actuator is chosen, it can be made to open and close the hot fluid valve directly in response to the temperature of the mixed fluid in which it is immersed. A similar application to this example is described in more detail in Case Study 3.2, page 135.

For our second example, let us consider conducting polymers in biomedical applications (see Chapter 6). Conducting polymers are soft ionic actuators. In order to actuate, they have to be immersed in an aqueous electrolyte. This requirement is usually a shortcoming rather than an advantage; in most applications, they require packaging solutions to keep the actuator wet during operation.

In the biomedical field, most applications are naturally realized in aqueous electrolytes (blood, urine, etc.). If other actuator technologies are to be applied under these conditions, they must be protected against these corrosive environments. However, it is the ideal environment for CP actuators.

1.6.4 Static performance

The static performance of actuators is typically evaluated on the basis of their available maximum effort (force or torque) and their maximum output velocity or stroke.

Blocking effort

The blocking effort is defined as the maximum effort (force or torque) that the actuator can deliver. This is the effort that will block the actuator so that no further displacement can be achieved against this load.

In the case of rotational actuators, the blocking effort is usually referred to as *stall torque*.

Maximum stroke

The maximum stroke (if any) of an actuator is the maximum available displacement that the actuator can deliver. It is the value of the displacement when no external load is applied on the actuator.

For most emerging actuators, the maximum stroke is given as a percentage of its length. In other actuators (pneumatic and hydraulic), it is limited by the particular configuration of the piston and is given as an absolute value.

Other actuators present no limit on the displacement they can attain. This is true of most rotational actuators (electromagnetic motors, ultrasonic motors, etc.). In these cases, the maximum rotational speed is commonly given.

1.6.5 Impact of environmental parameters

As noted earlier, for optimal use, actuators should be as insensitive as possible to external parameters. These typically involve temperature fluctuations, humidity changes and other external factors.

Temperature and temperature fluctuations have a direct undesired effect on most actuator technologies: there are upper limits on the temperatures that piezoelectric actuators can sustain because of depolarization; the electrical conductivity characteristics of ERF actuators can change as a result of temperature fluctuations.

Humidity has a direct effect on *wet* EAPs, so that there are strict packaging technology requirements unless the application is intrinsically wet.

1.7 A classification of actuator technologies

Actuators, as a particular category of transducers, can be classified according to a variety of criteria. Since the main function of an actuator in a mechatronic system is to establish a flow of energy between an input domain and the output domain, the first category heading is the sign of the power transmission.

Power is assumed to be positive when energy flows from the transducer to the plant and not vice versa. This classification, which categorizes actuators as semiactive or active devices, was introduced in an earlier section.

1.7.1 Semiactive versus active actuators

The power at the output port of the actuator can be expressed as a function of the conjugate variables as:

$$P_{Trans} = F \cdot v \quad (1.32)$$

for translational output mechanical energy, and:

$$P_{Rot} = T \cdot \omega \quad (1.33)$$

for rotational mechanical energy.

Semiactive actuators are those whose output mechanical power is not positive: $P_{Trans} \leq 0$ or $P_{Rot} \leq 0$. This means that the energy level in the plant is reduced. Semiactive actuators dissipate the energy of the plant they are coupled to.

Semiactive actuators can actively modulate power dissipation, but the effort they supply (whether a force or a torque) can only oppose the flow in the plant (whether a velocity or an angular rate).

Where semiactive actuators are used in motion control systems, these are known as *Semiactive motion control systems*. They are particular implementations of mechatronic systems in which the objective is to maintain the energy level of the plant within a bounded region. A typical example of a semiactive motion control system is the use of ER or MR fluid actuators for vibration isolation of delicate or fragile equipment from noise sources.

Semiactive control of vibrations, as the paradigmatic application of these systems, is analyzed in detail in Section 6.3. In addition, several instances of application to semiactive vibration isolation are analyzed in Case Studies 6.1 to 6.3.

Active actuators can either increase or decrease the energy level of the plant to which they are coupled. The power flow can be either positive or negative: $P_{Trans} \geq 0$ or $P_{Rot} \geq 0$.

Of the various different emerging actuators discussed in the book, only ERF and MRF actuators are classified as semiactive.

1.7.2 Translational versus rotational actuators

The conjugate variables used to define the power output in a translational actuator are the linear velocity, v and the force, f . The conjugate variables for rotational actuators are the angular rate, ω , and the torque, T .

Translational actuators convert electrical energy into translational mechanical energy, while *rotational actuators* convert electrical energy to rotational mechanical energy.

Rotational actuators are always obtained from geometrical transducers, for example, an electromagnetic DC motor. On the other hand, transducing materials generally produce translational actuators, for example, magnetostrictive actuators, unless some geometrical concept is added.

Depending on the type of motion resulting from the transduction process, *bending actuators* may also be considered (for instance, piezoelectric multimorph actuators). However, bending actuators are most often used in the context of driving linear plants.

In general, actuators of both types can be developed from geometrical concepts for all transducing materials. This applies particularly to piezoelectric actuators. Piezoelectric actuators lead, through different geometrical concepts, to rotational, translational and bending actuators.

1.7.3 Input energy domain

The classification according to the transduction principle (see Section 1.2) gives an idea of what classification according to input energy domain is like. Here, the

Table 1.2 Summary of actuator classification.

Type	Power flow		Output energy		Input energy domain				Force flow		
	Active	Semiactive	Linear	Rotational	Electric	Thermal	Magnetic	Chemical	Fluid	Soft	Hard
Piezoelectric actuators											
TWUM	X			X	X						X
TWLUM	X		X		X						X
Stacks	X		X		X						X
Inchworm	X		X		X						X
Multimorph	X			Bending	X						X
Shape memory actuators											
Mass load	X		X		X	X					X
Spring load	X		X		X	X					X
Antagonistic	X		X		X	X					X
Wet EAP actuators											
Polymer gels	X		X		X	X		X			X
IPMC actuators	X			Bending	X						X
CP actuators	X			Bending	X						X
Carbon nanotubes	X		X		X						X
Dry EAP actuators											
Electrostrictive	X		X		X						X
Dielectric elastomers	X		X		X						X
Field responsive fluid actuators											
MRF actuators		X	X		X					X	X
ERF actuators		X	X		X		X			X	X
Magnetostrictive actuators											
Magnetostriction	X		X				X				X
MSM actuators	X		X				X				X

output energy domain is restricted to the mechanical domain, without any further separation of energy types (rotational and translational).

There are five main input domains:

1. *Input electrical energy.* Most actuators belong to this category, particularly all piezoelectric actuators, electrostatic actuators, dry EAPs and ERF actuators.
2. *Thermal electrical energy.* This category includes SMA actuators, some wet EAP actuators (in particular, some Polymer Gels) and thermal bimetallic actuators.
3. *Magnetic electrical energy.* This category includes magnetostrictive actuators, MRF actuators and magnetic shape memory (MSM) actuators.
4. *Chemical input energy.* This category includes some wet (ionic) EAPs.
5. *Fluid input energy.* The pressure of a fluid in a chamber is used to provide the actuator force. This category includes *pneumatic* and *hydraulic* actuators. This domain, together with the thermal domain, is considered a particularization of the mechanical energy domain.

1.7.4 Soft versus hard actuators

Soft actuators, also called *pulling actuators*, are based on transducing materials configured in thin sheets or wires so that they can only withstand traction forces. The operative principle restricts the available forces to pulling:

$$f_{Soft} \geq 0 \quad (1.34)$$

Hard actuators, also known as *push-pull actuators*, have the ability to sustain both traction and compression forces:

$$f_{Hard} \geq 0 \quad (1.35)$$

Hard actuators are inherently two-directional actuators. Soft actuators are inherently unidirectional actuators but can be configured in antagonistic pairs to provide two-way actuation. This is commonly true of SMA actuators.

There are other possible classification criteria for actuators and transducers. For instance, actuators can also be classified according to whether the output motion is continuous or discontinuous. A classical example of discontinuous operation is electromagnetic or piezoelectric steppers. Table 1.2 summarizes the classification convention followed in this book.

1.8 Emerging versus traditional actuator technologies

Traditional actuators have been employed extensively during the last century in all application domains. The category of traditional actuators includes three

main technologies, namely, *Electromagnetic motors*, *pneumatic actuators* and *hydraulic actuators*.

Electromagnetic motors exploit Lorentz’s interaction between an electrical charge and a magnetic field in which it moves. In the case of a rotational motor, the transducer equation for this technology is

$$\begin{bmatrix} V \\ i \end{bmatrix} = \begin{bmatrix} 0 & g \\ -1/g & 0 \end{bmatrix} \begin{bmatrix} T \\ \omega \end{bmatrix} \tag{1.36}$$

These may be considered as gyrating transducers. In general, the applied voltage, V , will determine the rotational or translational velocity, ω or v , respectively. The current drawn is an indication of the torque or force applied at the mechanical port.

There are many different types of electromagnetic motors, but an exhaustive discussion of this technology lies outside the scope of this book. The reader is referred to any of the countless reference books on motion control hardware.

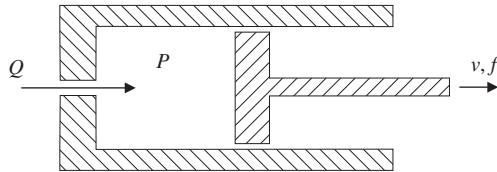


Figure 1.19 Transduction between fluid and mechanical domains, typical of pneumatic and hydraulic actuators.

Table 1.3 Comparison of traditional and emerging actuators.

Traditional actuators	Emerging actuators
Based on geometrical transducers	Based on transducing materials (possibly in combination with geometrical concept)
Off-the-shelf availability	Designed for the application
Good performance at normal scale	Good for meeting miniaturization demands
Lumped approach: discrete components in MCS	Integrated and embedded approach: open to smart structure concepts
Used in combination with external sensors	Pursuit of the smart actuator concept
Conventional mechanical transmissions for (output) impedance matching	New transmission designs based on hinges and friction
Incompatible with biomedical applications	Technologies (in some cases) ideally suited to biomedical applications

Pneumatic actuators exploit the power of a fluid (a gas, usually air) flowing into a chamber to develop a force (see Figure 1.19). The input energy is in the fluid domain. The power is defined by the volume flow rate, Q , and the pressure, P , as conjugate variables.

Hydraulic actuators are equivalent to pneumatic actuators in that the input energy is also in the fluid domain. The fluid is, however, an incompressible liquid (usually oil). For a linear actuator, the equation of the transducer is ideally

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} k & 0 \\ 0 & -1/k \end{bmatrix} \begin{bmatrix} f \\ v \end{bmatrix} \quad (1.37)$$

where k is the effective area of the pneumatic cylinder.

Emerging actuators are those driving technologies developed from novel (or when old, newly developed) transducer materials. They are analyzed in detail throughout this book. Table 1.3 compares traditional and emerging actuators.

1.9 Scope of the book: emerging actuators

This book is devoted to the analysis of emerging actuators as constituents of motion control mechatronic systems, and as mechatronic systems on their own. The electromechanical design, particular control concepts and exploitation of the smart actuator approach is therefore analyzed for each technology.

The analysis is divided into five chapters dealing with five transduction technologies and the actuator concepts based on these technologies. The transducing materials are the following:

1. *Piezoelectric ceramics*, Chapter 2.
2. *Shape memory alloys*, Chapter 3.
3. *Electroactive polymers*, Chapter 4.
4. *Magnetostrictive materials*, Chapter 5.
5. *Electro- and magnetorheological fluids*, Chapter 6.

The following aspects are addressed for each transducing material:

- detailed description of transduction principles and characteristics;
- analysis of constitutive equations for the transducer and the actuator concepts;
- mechatronic aspects of actuator design;
- control aspects of particular relevance for each technology;
- figures of merit and scaling properties; and
- relevant illustrative applications.

The last chapter of this book summarizes the most salient issues of each emerging actuator technology and presents the comparative position of the various different actuator technologies. Here, traditional actuators are discussed for reference purposes. Particular emphasis is placed on trends in applications and on open research issues.

1.10 Other actuator technologies

1.10.1 Electrostatic actuators

Electrostatic actuators are relatively novel devices whose operating principle is based on electrostatic attractive and repulsive forces between electrical charges. As such, they exhibit the same operating principle as Dielectric Elastomer actuators (see Chapter 4).

Basics of electrostatic interaction and actuators

The basic configuration of an electrostatic actuator is that of a capacitor of variable capacitance, C . The capacitance of a flat, parallel plate capacitor is:

$$C = \varepsilon \frac{A}{d} \tag{1.38}$$

The constitutive equations for the electrostatic actuator can be developed from the expression of the electrical power, P , stored in the capacitor. The power can be obtained from the time rate change of the stored electrical energy, $P = dW/dt$. The electrical energy for a capacitor with an applied electric field E is

$$W = \frac{q^2}{2C} = \frac{1}{2} \varepsilon E^2 V = \frac{1}{2} \varepsilon E^2 ayx \tag{1.39}$$

where q is the electrical charge at the capacitor plates, V is the volume of the dielectric between the plates and the other dimensions are as in Figure 1.20.

If a variable gap capacitor is considered, the resulting expression for the power will be

$$P = \frac{dW}{dt} = \frac{\partial W}{\partial x} \frac{dx}{dt} + \frac{\partial W}{\partial q} \frac{dq}{dt} \tag{1.40}$$

In Equation 1.40, the term dx/dt is the velocity of the moving plate and dq/dt is the electrical current used to charge the capacitor. Since the result of the two terms at the right-hand side of the equation must be a power, it follows that $\frac{\partial W}{\partial x}$ must be the electrostatic force on the moving plate, F_{\perp} , and $\frac{\partial W}{\partial q}$ must be the voltage across the capacitor, U .

If we use Equation 1.39 together with the previous results, it follows that

$$F_{\perp} = \frac{\partial W}{\partial x} = \frac{1}{2} \varepsilon E^2 ay \tag{1.41}$$

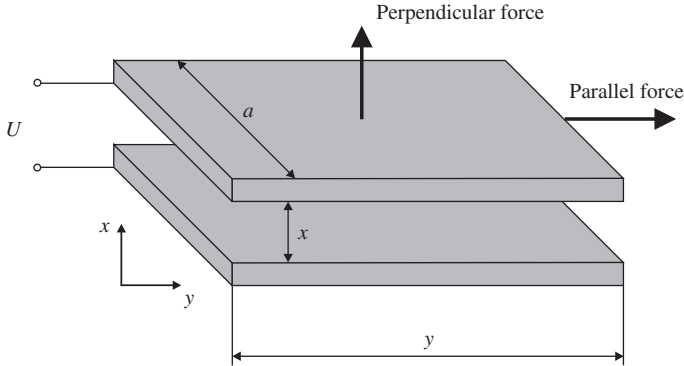


Figure 1.20 Schematic representation of a variable capacitance electrostatic actuator.

and

$$U = \frac{\partial W}{\partial q} = \frac{q}{C} \quad (1.42)$$

Here, let us consider a case in which the variable capacitance configuration is obtained by a modification of the capacitor's effective area while maintaining the gap. If this is achieved by sliding one of the plates sidwise in the direction of y (see Figure 1.20), the expression for the force is

$$F_{\parallel} = \frac{\partial W}{\partial y} = \frac{1}{2} \varepsilon E^2 a x \quad (1.43)$$

Equations 1.41 and 1.43 can be rewritten in terms of the applied voltage:

$$F_{\parallel} = \frac{1}{2} \varepsilon U^2 \frac{a}{x} \quad \text{and} \quad F_{\perp} = \frac{1}{2} \varepsilon U^2 \frac{a y}{x^2} \quad (1.44)$$

A simple inspection of Equation 1.44, will readily show the following.

1. *Electrostatic interaction is short range.* The magnitude of the electrostatic forces decrease rapidly when the actuator is scaled up.
2. *Perpendicular forces are much higher than parallel forces.* In most, $F_{\perp} \approx 10^3 F_{\parallel}$.
3. *Electrostatic interaction is appropriate for microapplications.*
4. *Complementarity in force and stroke.* Actuators based on perpendicular and parallel forces are complementary in force and stroke. In perpendicular actuators, the stroke is limited at most to the size of the gap.

Actuator configurations

Electrostatic actuators exploit either perpendicular, F_{\perp} , or parallel forces, F_{\parallel} . In parallel configurations, the most common developments are the ones known as *comb drives*.

In comb drives, two comblike structures are used. The pins in each comb structure are used as electrodes in a layered capacitor configuration. The parallel-type electrostatic forces tend to pull both combs together. The combination of multiple layers and the symmetry of the structure is used to balance out the perpendicular interaction so that F_{\perp} on each pin would ideally cancel out.

Comb drives can be used to develop both linear and rotational actuators. Figure 1.21 illustrates the two concepts. In both cases, the parallel force generated by the electrostatic interaction results in interdigital rotational and translational movements.

The other typical configuration for electrostatic actuators is one that exploits perpendicular forces. This configuration is illustrated by the tilt mechanism of microscope mirrors as depicted in Figure 1.22. The mirrors can be rotated around a torsional hinge (light white in Figure 1.22b) as a consequence of the electrostatic force of perpendicular force actuators.

1.10.2 Thermal actuators

Thermal actuators are based on the thermal expansion of materials, either in solids or gases. SMA actuators (see Chapter 3), and some polymer gel actuators (see Chapter 4), can be considered thermal actuators as well as actuators based on thermal expansion.

However, the term thermal actuators usually refers to multimorph-type thermally activated actuators. These actuators exploit the difference in thermal expansion coefficients of two dissimilar metals bonded together to produce bending deformations of the composite structure.

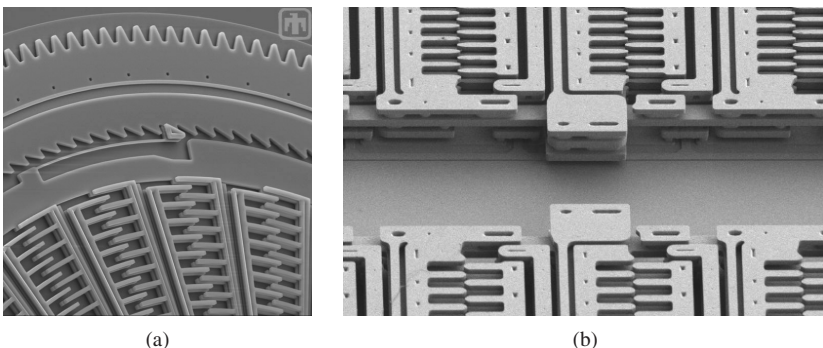


Figure 1.21 Electrostatic comb drive actuators: (a) Rotational actuator in combination with a ratchet and (b) detailed view of a linear actuator structure.

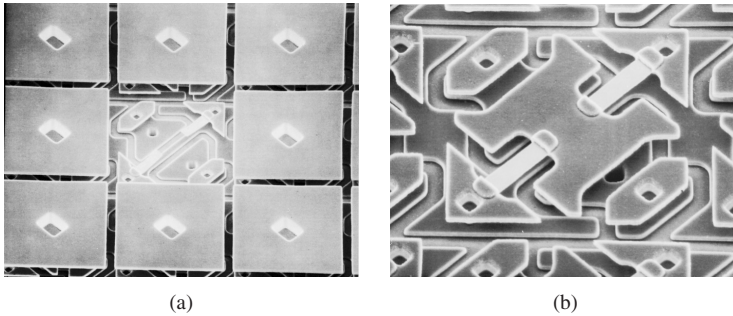


Figure 1.22 Matrix of controlled tilt mirrors for optical deflection. Each pixel is 16 μm in width and is mounted on electrostatic actuators.

Thermal actuators are limited by the long response time of the heat transport process required for actuation. The force available in a thermal actuator is proportional to L^2 , where L is the dominant dimension of the actuator. Similarly, the available stroke is usually expressed as a percentage of the actuator length and thus scales as L .

From the force and stroke, it follows that the available work per cycle and the available work density per cycle scale in proportion to L^3 and L^0 respectively.

In thermal systems, the time taken to transport the heat and actuate the system is proportional to the mass of the actuator, L^3 , and inversely proportional to the heat rate. According to Peirs (2001), the heat rate scales proportionally to L . Therefore, the time constant of thermal systems scales in proportion to L^2 .

This means that reducing the scale of the actuator by a factor of 10 will produce systems that are 100 times faster. As calculated above, the power density is proportional to L^{-2} and thus also increases by a factor of 100 when the actuator is scaled down by a factor of 10.

All these results suggest that thermal actuators are an appropriate technology for integration in microsystems. Figure 1.23 shows a thermal actuator in a microsystems application.

1.10.3 Magnetic shape memory actuators

A martensitic transformation is a first-order, diffusionless transformation exhibited by some alloys (Fe, Cu and Ti alloys). The martensitic transformation is affected by a variety of external fields (temperature, uniaxial stress, hydrostatic pressure and magnetic fields) and is the basis of various different emerging actuator mechanisms. In the context of thermally triggered martensitic transformations in Ti-based alloys in particular, we would highlight the case of shape memory alloy actuators (see Chapter 3 for a detailed discussion of SMA actuators and martensitic transformations).

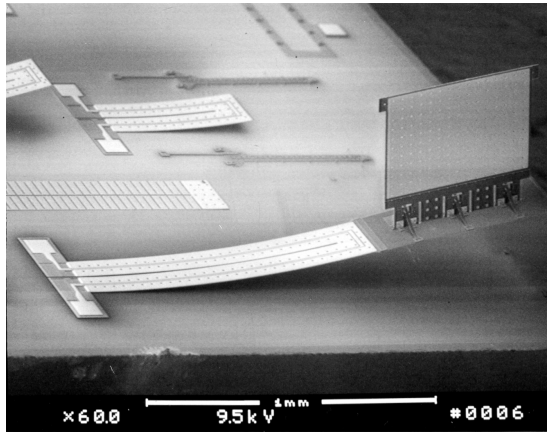


Figure 1.23 SEM photograph of a vertical thermal bimetallic actuator with integrated micromirror. The application of a current to the actuator arm produces vertical motion of the mirror, which can either reflect an optical beam or allow it to be transmitted (Photograph courtesy of Joseph N. Mitchell, Southwest Research Institute).

In this section, we will briefly address the case of actuators based on martensitic transformations triggered by magnetic fields, which are known as *ferromagnetic shape memory alloy actuators*, *FSMAs* or *magnetic shape memory actuators*, *MSMAs*. As in the case of thermally triggered shape memory actuators, the transformation is possible because of the difference in magnetic moment between the parent and the martensite variants.

The mechanism of actuation with MSMAs is similar to the mechanism with thermal shape memory actuators. The ferromagnetic shape memory alloy consists of internal domains and twin variants, which have different crystallographic and magnetic orientations. In the martensite phase, when no external magnetic field is applied, the twin variants are preferentially aligned (by means of a bias load). The shortest, magnetically active axis in the crystallographic lattice is generally oriented in the direction of actuation (see Figure 1.24, left).

When a magnetic field is applied perpendicular to the magnetically active axis, the other twin variants appear and grow. As a direct consequence, the magnetically active axis (which is the shortest in the lattice) of these new variants is aligned perpendicular to the direction of actuation and the length of the specimen increases (see Figure 1.24, right). The maximum attainable stroke is defined by the ratio of the length of the long to the short axis in the lattice, a/c .

For the magnetic shape memory effect to materialize, the magnetic anisotropy energy of these alloys must be larger than the elastic or frictional energy associated with the conversion of variants. As in the case of thermally triggered shape memory actuators, MSMAs are one-way actuators and must be configured against bias

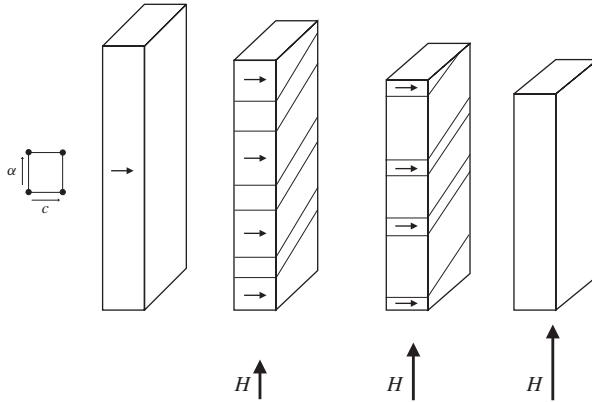


Figure 1.24 Schematic representation of the magnetic shape memory mechanism.

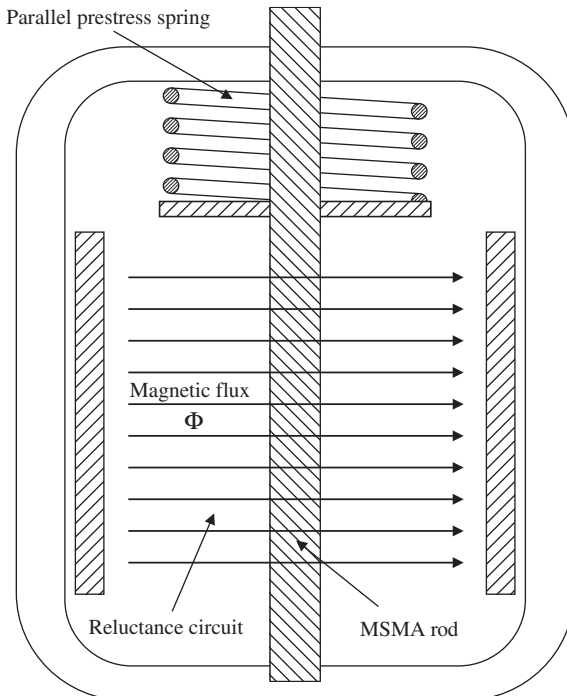


Figure 1.25 Components in MSMA: bias loading springs, MSMA rod and reluctance circuit.

loading in order to complete the actuation cycle. Again, magnetic SMAs can be made to change their shape in response to axial, bending or torsional loading.

The basic structure of a magnetic shape memory actuator is depicted in Figure 1.25. The actuator includes components to prestress the magnetic SMA specimen (usually based on linear springs as shown in the figure) and components to set up the magnetic field perpendicular to the direction of actuation. The reader is referred to Chapter 6 for more details regarding the design of reluctance circuits to set up the magnetic field.

Magnetic shape memory actuators are a special class of giant magnetostrictive actuators, which can therefore be classified into two broad categories: Joule magnetostrictive actuators and twin-induced magnetostrictive actuators. On the one hand, magnetostriction based on the Joule effect has been known since the nineteenth century and is dealt with in detail in Chapter 5. On the other hand, the property known as twin-induced magnetostriction was discovered much more recently (in the 1960s, see Kakeshita and Ullakko (2002)) and is only now gaining some momentum.

Joule-based magnetostriction is characterized by higher forces (only a few N have been achieved in MSMA's so far) and frequency of actuation, higher Curie temperatures (about 380 C as compared to only 100 C in twin-induced magnetostrictive materials) and smaller driving magnetic fields (usually half that required in MSMA's), fatigue and hysteresis.

Twin-induced magnetostriction is characterized by a higher stroke (up to 50,000 ppm, as compared to 1700 ppm in Terfenol-D, see Chapter 5) and higher energy output per cycle (three times that of Terfenol-D). The first prototypes of MSMA's were not developed until recently; they are currently at a promising experimental stage. Some of these prototype implementations will be introduced in more detail in a case study in Chapter 5.