Chapter 1

Design of Integrated Flexible Structures for Micromanipulation

The design of robotic micromanipulators relies on flexible mechanical structures. These are increasingly being used due to their integration of actuator and measuring functions. The general design context for these integrated systems has resulted in a complex and multi-disciplinary approach to the problem. This design exploits structures' flexibility to respond to the challenges of robotic manipulation on a microworld scale. The design analysis approach is used in fields ranging from material sciences to advanced automatic control and topological structural optimization. In this chapter, the need for optimal design aid tools for these systems will be clearly highlighted and a range of existing optimization strategies will be examined. Finally, an illustrative example that focuses on the development of an optimal design software tool for flexible monolithic structures, will conclude the chapter. These structures are capable of maintaining actuator and sensor functions in a distributed and integrated form using piezoelectric materials.

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1.1. Design and control problems for flexible structures in micromanipulation

The efforts made in Japan and the United States at the beginning of the 1990s in system miniaturization and integration have resulted in the concept of the *micro*. Whether in electronic devices for use by the general public or microcomputers or pioneering devices in mini invasive surgery, all these systems integrate several functional components (mechanical, optical, electric, etc.) in a more or less restricted space to create a microsystem, also known as a Micro-Electro-Mechanical System (MEMS) or Micro-Opto-Electro-Mechanical-System (MOEMS) if it features optical functions. The concept of a microbot is the result of a combination of microsystems and robotics. Its principle aim is to cause necessary movements to move and direct one or several tools to carry out a task in the microworld, a world of objects on a micrometric scale.

Microsystems carry out technological functions of different kinds, whether mechanical, thermal, electrical or optical. They cover a vast sphere of applications in a number of domains (biomedical, automobile, optical, micromanipulation, etc.). As with robots, the microbot is a mechatronic system controlled on site which is reprogrammable, able to make movements in relation to a specific environment and even interact with it. It includes perceptive, environmental action and information processing functions. In addition, it adopts its dimension and resolution specifications from this microsystem. In its strictest sense, the use of the *micro* prefix refers to a micron (10^{-6} m), although the dimensional objective often lies between a millimeter and a centimeter [BOU 02]. If not strictly micrometric in size, a microbot can be qualified as such when it has at least one of the following characteristics [REG 10]:

– It uses micrometric components (microsensors, micro-actuators, etc.).

– It uses micrometric objects or, more generally, carries out tasks within the microscale, that is the world of micro-objects.

– It has high positioning resolutions of less than a micron (the study and creation of high-resolution robots, of the order of 100 nm or less, has often resulted in robots characterized by their small size and a reduced final size due to the constructive principle used).

As a result, the definition of microbots and, more generally, microsystems gives them a wide applicable field. The design and control of microbotic devices dedicated to micromanipulation tasks constitute the core of this chapter.

Micromanipulation relates to the use of an external force to carry out tasks such as picking up and dropping, pushing, cutting and assembling objects whose dimensions range from the micrometer to a millimeter. The creation of the robotic micromanipulation, devices by miniaturizing robotic manipulators, as known on the microscopic scale, is often not possible because the reduction of the scale applied to robots' functional components faces technological barriers. Miniaturization attempts must, therefore, take place in several fields:

– micromechanics, as well as the study of manufacturing and micro-assembly procedures dedicated to microworld scales;

– actuators (for the application of forces and movements in volumes in the order of cubic centimeters, cm^3), notably in strength and position sensors (small in size but with a high-resolution); control and implementation within computational parts.

Miniaturization cannot be reduced to a simple reduction in scale of existing components, but demands the complete reconsideration of robots' major functions and technological means to implement them. In particular, other means of actuating and measuring must be studied with regard to their physical principle as well as their good adaptability to the microworld in terms of movement, forces, mechanical force, output, controllability, observability, etc.

1.1.1. *Characteristics of manipulation on the microscale*

In the context of microbotics, measuring information from the micrometric world is a problem that raises a number of challenges. Indeed, due to the scale factor, the dynamic behavior of micro-objects is no longer governed by their mass (which is an effect of volume), but surface effects that correspond to adhesive forces (surface tension, electrostatic and van der Waals forces). The dynamic of this kind of micrometric environment differs completely from that of the standard metric world. In addition, these adhesive forces are generally dependent on the type of context (dry or liquid environment) which are variable over time (tribo-electrification, modification of environmental conditions, humidity and temperature) and in space (types of materials in contact, geometry and local roughness). In these conditions, the understanding and prediction of micro-objects' dynamic behavior requires at least knowing their position in the microworld and, in addition, knowing the amplitude and gradient of the forces being exerted on them.

The notion of the microworld is currently used to define a space (world) with specific characteristics. This is a world where objects with sizes ranging from 1 μm to 1 mm evolve. In comparison, the "microworld" is the term adopted to indicate a world of objects that exceeds a millimeter in size. Interactions between objects in the microworld are governed by the laws of "microphysics" . This term indicates that the laws governing the behavior of objects in the microworld are different to those in the macroworld. This is not the case in reality and the difference lies in the fact that forces, which are completely unnoticeable on the macroscopic scale, become paramount due to the objects' reduced size. The surface effects, therefore, play a more important role than volume effects. To highlight this difference, we will take two spheres with a diameter of 20 μm and 20 mm, respectively. The calculation of the ratio between the surface and volume, which is equal to $3/r$[1], is 300,000 and 300 for each sphere. As a result, surface forces (surface tension and electrostatic forces) are much more significant in relation to volume-related forces (weight) on the sphere with a diameter of 20 μm compared with 20 mm.

In everyday life, a large number of examples attest to the influence of surface forces in the microworld. The most obvious example is that of a mosquito which can rest on the ceiling. This is possible when the adhesive forces (surface forces) between the insect's feet and the ceiling are significant enough to counter balance its own weight (volume force). A second example is that of a human who wants to pick up a small object (i.e. a needle). Very often, and sometimes unconsciously, s/he moistens her/his finger to pick up the object more easily using adhesion by surface tension as this process increases the adhesive forces between the needle and her/his finger.

1 *r* being the radius of the sphere in question.

1.1.2. *Reliability and positioning precision*

Regardless of the performance in terms of the precision and resolution inherent to the technological choice of actuator and sensor or, more generally, the chain of control, the absolute precision of positioning in robotic systems is generally limited by its mechanical structure, manufacturing faults and potential mechanical challenges in managing mechanical play or backlash in joints that introduce systematic errors. If the precision of the positioning of such systems can generally result in the precise manipulation of millimetric objects, it becomes unacceptable in the more constrained context of micromanipulation, where the resolution required is sub-micrometric.

To overcome this lack of precision, compliant structures are of particular interest. This shape can prove undesirable on the macroscopic scale because it adds small, unpredicted and difficult-to-control movements which can nevertheless be used to an advantage on a micromanipulation scale. The use of the mechanical structure's shape can be interesting from the perspective of a precise position and guiding. This is the object of study in compliant structures. These structures are often composed of a single compliant body (without any kinematic connection) and are known as monolithic. The coexistence of varied components such as actuators and sensors in the microsystem requires managing micrometric scale assembly technologies to allow a superior final design in the robotic system. Functional challenges and surface states demand manufacturing tolerances which become increasingly difficult to respect on the mesoscopic scale. Whether serial or parallel, it has been shown that microassembly is the most costly aspect in the production of microsystems (up to 80%) [KOE 99]. As a result, the reduction, or even absence, of assembly is still being researched by the micromechatronic system designers.

The manufacturing process often needs to be reconsidered to adapt it to dimensional constraints and account for interactions between the system and its environment. Standard system design methods (chip manufacturing, for example) cannot be fully applied to microsystems. Manufacturing microtechnologies from the field of microelectronics has provided the first solutions to creat microsystem prototypes. Today, depending on the nature of components and their materials, there are several solutions such as silicon microtechnologies and, more recently, new technologies allowing tridimensional manufacturing such as 3D laser production, ultrasonic manufacturing, micromoulding and microstereolithography.

Monolithic compliant mechanisms do not pose the usual problems of assembly encountered during the mechanism fabrication stage and increases the mechanism's precision due to the absence of friction in terms of articulations. There are two types of compliant structures:

– Structures whose deformations are restricted to several specific points in the structure. These are generally rigid structures connected by flexible joints (Figure 1.1). The behavior of these flexible connections is comparable to the pivot kinematic connection. However, the major disadvantage of these flexible guidings lies in their limited lifespan due to the appearance of a zone with concentrations of constraints, notably in the flexure hinge (Figure 1.2).

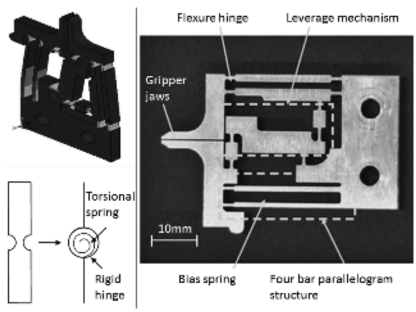


Figure 1.1. *Gripper with a flexure hinge structure [ZUB 09]*

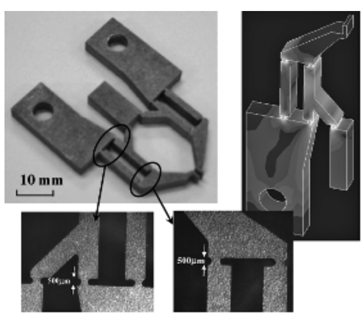


Figure 1.2. *Microgripper with flexure hinges (representation of constraints) [NAH 07]*

– Distributed compliant structures (Figure 1.3); while they do not generally present the previously cited disadvantage, their design is much less intuitive and relies on the optimization methods to determine their shape or topology (Figure 1.4).

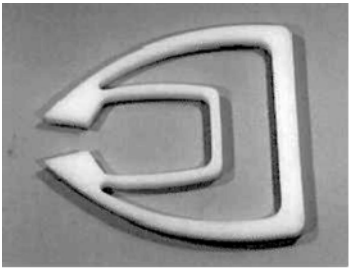


Figure 1.3. *Structure with shared deformation distribution [KOT 99]*

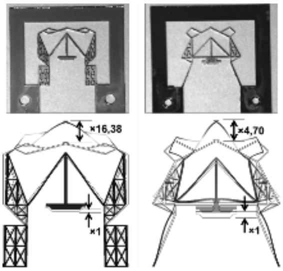


Figure 1.4. *Silicon microamplifiers for a PZT actuator (shaped and viewed from MEB) [GRO 07a]*

1.1.3. *Micromanipulation station*

Micromanipulation can be carried out in three different types of environments: in a vacuum, in air and in liquid. The choice of working environment is essentially governed by the nature of objects being manipulated. Micromanipulation tasks are carried out from a micromanipulation site. The elements which constitute a micromanipulation site include:

– effectors and manipulators adapted to the specific characteristics of the micro-objects to be manipulated (Figures 1.5 and 1.6);

Figure 1.5. *Example of Microprehensile Microrobot On Chip (MMOC) and its Nickel effector parts [AGN 05]*

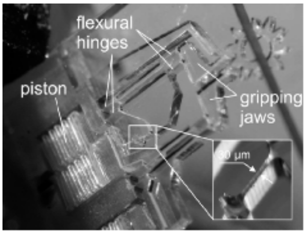


Figure 1.6. *Example of a flexible neck microgripper with a micropneumatic actuator [BUT 02]*

– one or several positioning axes. These cause the movement of a manipulator or even the work surface when the manipulator's movement is not possible. Because of the specific nature of micromanipulation actuators must have positioning resolutions with a minimum order of a micrometer;

– one or several vision and visualization devices (microscopes, cameras and screens). These devices are necessary due to the size of objects being manipulated. They therefore provide a close-up image of the microworld;

– a human–machine interface (HMI). This device, software and material, is required on a site because it creates a bridge between the micro and macroworld. Often, the devices used are haptic interfaces composed of mechanical structures with multiple degrees of freedom. In addition to providing the operator with real manipulation opportunities, these devices provide the potential of "feeling" the interactions with the objects being manipulated (contact/detachment forces, gripping forces, etc.). As a result, to complete this process, this supports the use of virtual or augmented reality methods;

– one or several controllers whose function controls state variables (position, speed, temperature, etc.).

Parasitic elements such as chips (comparable to micro-objects in size), air flow, humidity and ambient temperature can prevent the correct function of micromanipulation tasks. To respond to these challenges, an initial solution may include using a controlled environment site. A second, complimentary solution entails monitoring the situation using a viewing system to control the trajectories and even avoid collisions. The use of forces used during the micromanipulation phases, therefore, generally improves the chances of success. Given the significant recent advances in microbotics, remotely controlled microassembly sites have been the subject of recent developments (Figures 1.7 and 1.8).

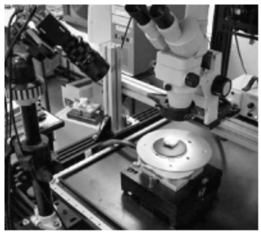


Figure 1.7. *Micromanipulation site with a camera and microscope [SHA 05]*

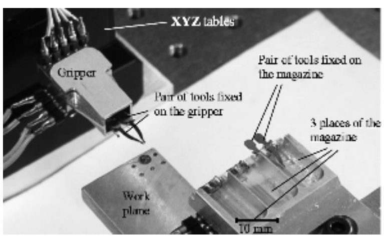


Figure 1.8. *Site allowing the change of terminal parts [CLE 05]*

1.1.4. *Difficulties related to controlling robotic micromanipulators*

The control of gripping microsystems is difficult due to different concurrent factors (Figure 1.9).

1.1.4.1. *System behavior*

The specific effects of scale in the microworld render the analysis and creation of dynamic and kinematic models difficult because movements are often unpredictable. The dynamic behavior of the actuators used is strongly nonlinear (notably phenomena such as hysteresis and slow drift), which often results in a complication of control laws. In addition, the materials composing part or all of the system being controlled often remain sensitive to environmental test conditions. Indeed, the influence and variability of the environment can be great in terms of variations in temperature, humidity, electrical charge and external disturbances (such as mechanical vibrations and light rays). Finally, the dynamics of microsystems are highly variable from one actuator and measuring technology to another. In particular, actuators based on the use of active materials such as piezoelectric ceramics, which are today undoubtedly the most common materials used to monitor micromanipulators, can have accelerations in the order of 10^6 ms^{-2}. In contrast, the time constants involve in actuators based on the use of shape memory alloys (SMAs) of around 1 s.

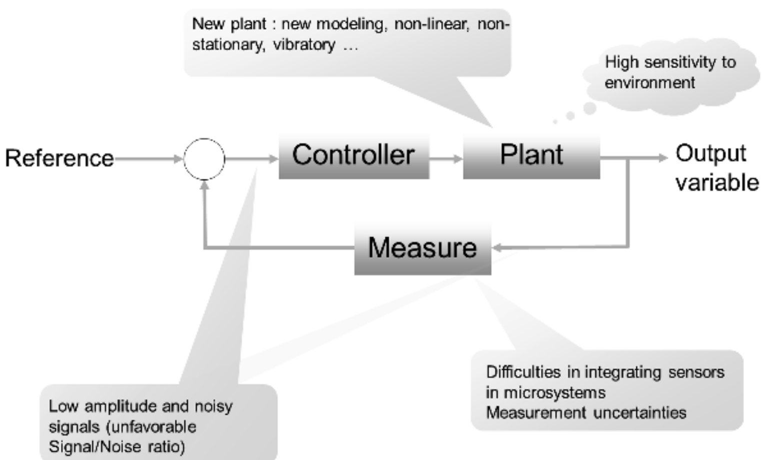


Figure 1.9. *Anatomy of a retroaction in the microworld [HAD 11]*

1.1.4.2. *Measuring system*

The difficulties of integrating precise and high-performance sensors into microsystems prevent a direct proprioceptive measure of the major values used for control. The creation of a sensor must go hand-in-hand with that of the system and remains a significant technological challenge. Some microsystems, therefore, operate within an open loop or are remotely operated in the case of micromanipulation tasks. The output of information is here ensured by an external system, most commonly by a supervision system using a microscope and/or a camera fitted around the work station. In addition, the signals used, often with low amplitudes and disturbed by environmental conditions, require numerical processing prior to their use within the control loop.

1.1.4.3. *Challenges of mechanical flexibility*

In addition to the previously cited difficulties, there are effects related to the mechanical deformation used for microprehension structures. Flexible mechanical structures have a field of deformations and constraints which depend on their topology and the nature of materials used. The coupling between mass and stiffness, related to an exchange between kinetic and elastic deformation energies, results in oscillating dynamic behavior similar to that of a system composed of several spring-mass systems. The resulting resonances, which are characterized by a natural frequency and modal shape, depend on the distribution of mass in the structure and the range of mechanical parameters. In the practical context of micromanipulation, vibrations resulting from structural flexibility are a source of problems which could affect the operation of these systems. These effects must therefore be mitigated or even suppressed.

1.2. Integrated design in micromechatronics

When operating a reduction in scale in commonly encountered mechatronic systems in the macroworld, miniaturization is necessarily accompanied by a functional integration of these systems. This general tendency forces robotic micromanipulators to possess an increasingly significant functional density. As with macroscopic scale manipulator robots, the robotic micromanipulator must possess actuator and measuring functions as well as a mechanical structure capable of ensuring and/or transmitting movements necessary for carrying out a task programmed in the microworld. The general framework of the design approach for these systems results in a complex and multi-disciplinary approach to this problem. This design benefits from the structural flexibility to respond to the challenges of robotic manipulation at this scale. The design analysis approach is used in fields ranging from the material sciences to the robust automatic control and topological structural optimization.

1.2.1. *Modeling integrated flexible structures*

Micromechatronic systems used for micromanipulation often employ a basic compliant mechanical structure. Their behavior therefore quickly proves highly complex to model and solve analytically. Given the simulation stages, a complete mathematical model of the system must first be established. On the basis of this model, the simulation of its closed-loop operation is made to qualify the performance, stability and robustness of the controlled system before the numerical implementation of the corrector into the prototype system. The design of a flexible structure can be analyzed according to different stages (Figure 1.10).

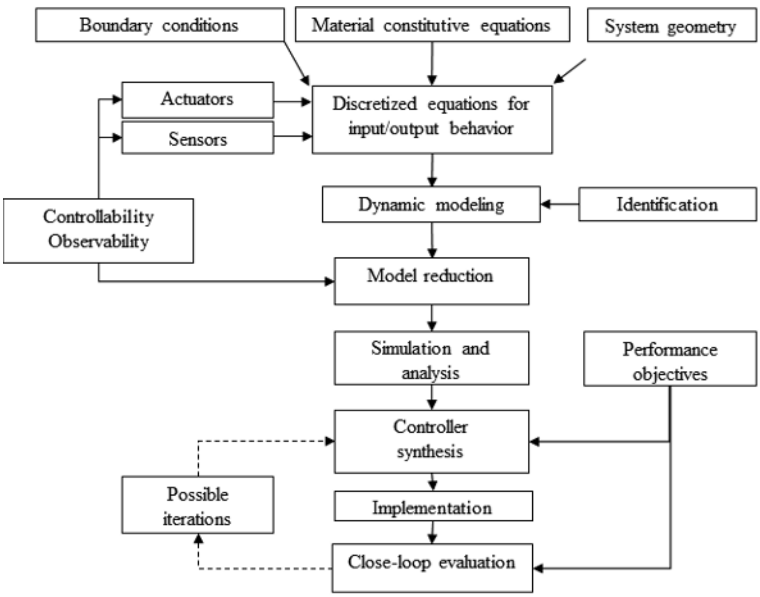


Figure 1.10. *Design and simulation stages [JAN 07]*

1.2.2. *Active transduction materials*

The efforts made toward an integrated design for prehension microsystems have resulted in the use of active materials as a means of adding an additional stage into the integration of these systems. The joint use of mechatronics and advances in the field of active materials results in the concept of adaptronics. The generic term adaptronic relates to the more commonly known terms such as *smart structures, smart materials, intelligent systems, adaptive structures* or even *active structures* [HUR 06]. The notion of adaptronics indicates “a system (and its development stage) in which all the functional elements in a regulation circuit coexist, in which at least one element is applied multifunctionally” [JAN 07]. The distinction, which can be made using traditional control schemas, in which each function is ensured by an independent elementary component, is fixed by the use of multifunctional elements. The existence of such elements is made possible by the use of active materials which play a major role in the technological creation of these systems. Overall, they render the system less complex structurally and integrate, at most, its different functional elements. This, therefore, raises the problem of optimal location and the physical integration of actuators and sensors in the flexible structure (Figure 1.11).

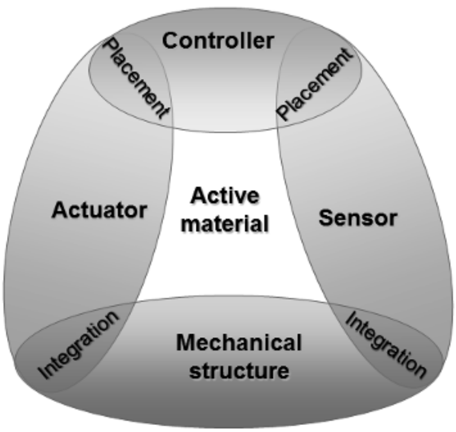


Figure 1.11. *Functional integration using active material [JAN 07]*

Adaptronics therefore results from the synergy between mechatronics and active materials to create systems of high functional density by integrating actuator and/or measuring functions into the structure when required by an environmental change (such as a constraint, an electrical or magnetic field and variation in temperature) or, more generally, by control signals (such as electrical or magnetic signals). The material therefore fulfills several functions and the basic components of the control loop are no longer physically independent.

The choice of actuator and sensor when designing a prehension microsystem is made using a number of performance criteria and constraints: stationarity, linearity, precision, resolution, sensitivity, reversibility, cost, etc. The remainder of this section describes some active materials which are currently used in micromechanics, classified according to the type of transduction in question.

1.2.2.1. *Electrical transduction*

1.2.2.1.1. Piezoelectricity

"Direct" piezoelectric effect is a phenomenon where electrical charges appear on the surface of a material when it is subject to mechanical constraints. The "opposite" effect produces a deformation in the material when an electrical field is applied to it. The electromechanical coupling coefficients in these materials transmit this energy conversion. Their performances in terms of high-resolution and speed render it the actuator of choice in microsystem design. The transmitted forces therefore remain largely greater than in other actuator types. In some conditions of use, electromechanical relations can be considered linear. A major disadvantage of this material is its poor deformation, in the order of 0.1%. In actuator mode, it is composed principally of unimorphic (Figure 1.12) and bimorphic structures. However, there are a number of active piezoelectric structures in less intuitive forms (Figure 1.13).

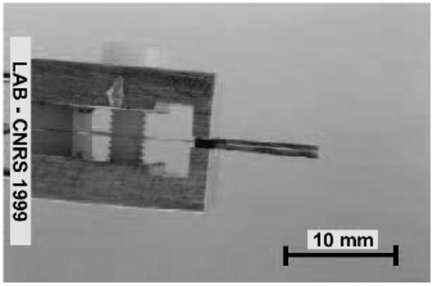


Figure 1.12. *Microgripper with unimorphic piezoelectric beams [HAD 00]*

1.2.2.1.2. Electrostriction

Electrostriction is another phenomenon that allows solid objects to be shaped when an electrical field is applied to them. The relationship between the applied field and the material's deformation is quadratic. Despite their low length of hysteresis, electrostrictive materials have often been abandoned in favor of piezoelectric materials because their deformation remains too sensitive to the influence of temperature.

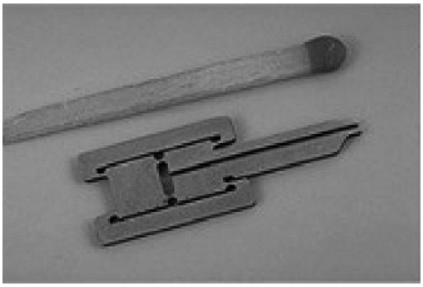


Figure 1.13. *Massive monolithic piezoelectric microgripper [BRE 97]*

1.2.2.1.3. Electroactive polymers

Electroactive polymers are those polymers which show deformations when subject to an electrical field. The deformation produced is relatively large in comparison to other electroactive materials; in contrast, the forces created are low. Moreover, polymers have the advantage of being flexible and often biocompatible while requiring a relatively low voltage [CHA 03].

1.2.2.1.4. Electrorheological fluid

Electrorheological fluids are composed of a dielectrical fluid carrying semi-conductor particles whose size is between 0.04 μm and 100 μm with a general volumic fraction[2] in the order of 20–30%. Depending on the electrical field applied, the rheological properties (viscosity, threshold constraint, etc.) of an electrorheological fluid are altered considerably.

1.2.2.2. *Magnetomechanical transduction*

1.2.2.2.1. Magnetostriction

Magnetostriction is the ability of a material to be shaped by an external magnetic field. It occurs in all ferromagnetic materials but provides an increased magnetostrictive effect.

2 Ratio between the volume of particles and the total volume.

1.2.2.2.2. Magnetorheological fluids

Magnetorheological fluids contain suspensions of ferromagnetic particles in an organic or aqueous liquid. In the absence of a magnetic field, these fluids are generally well described by the flow of Newtonian fluids that are characterized by their viscosity. When a magnetic field is applied, a Bingham plasticity model characterizes the fluid according to its shear constraint. It signals that such fluids, similar to electrorheological fluids, are semi-active materials, that is they can only divert energy and not convert it. Their main applications are, therefore, controllable buffers or, more recently, semi-active haptic interfaces [LOZ 07].

1.2.2.3. *Thermomechanical transduction*

1.2.2.3.1. Thermal dilatation

Thermal dilation in a solid object is used to generate a mechanical task. In the microworld, this principle is widely used with bimetallic or, more generally, multimorphic structures that are composed of several solid layers that are themselves distinct thermal coefficients. The differences in dilation result from the effect of temperature that causes an overall flexion in the composite structure. Thermal actuators have the disadvantage of having low time constants and being subject to heat dissipation problems.

1.2.2.3.2. Thermal expansion of gas

A specific interpretation of perfect gases' state equations can be used to create microactuators: under constant pressure, a gas trapped in an initial volume chamber is heated which thus increases the volume.

1.2.2.3.3. Shape memory alloys

In SMAs, a variation in temperature causes a change in the solid–solid phase of the material which results in a significant alteration in the crystalline network whose shear stress is its essential component. Notable deformations which may be obtained are in the order of 6% in traction with blocking constraints which can range up to 250 MPa. After permanent low-temperature deformation, SMAs return to their initial non-deformed shape by heating which is their form memory aspect (Figure 1.14). In actuator mode, the implementation of the heating control can be simply made by exploiting the Joule effect using the movement of an electrical current in the SMA or, as proposed by [BEL 98], by laser cutting (Figure 1.15). However, the deformation induced by thermomechanical phenomena gives these materials a relatively slow response time (the bandwidth does not exceed 1 Hz for an SMA wire of 150 μm in diameter). As a result, their thermomechanical behavior is strongly nonlinear.

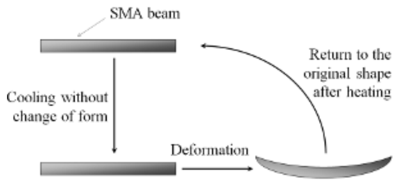


Figure 1.14. *Illustration of the shape memory effect*

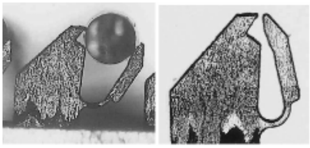


Figure 1.15. *Monolithic SMA microgripper in open and closed position [BEL 98]*

1.2.3. *Multiphysical models*

The integration of multifunctional materials in a mechanical structure requires taking into account the multiphysical coupling in the model's creation. The starting point of the model is the constituent relationship of the material considered by making the general hypothesis of a linear elastic *continuum*. The structure's dynamic is formulated using the generalized Hamiltonian principle that expresses a variational function of the problem in an energy form by considering the multiphysical coupling within the system [HE 01]. Kinematic constraint–displacement hypotheses about the mechanical structure are, therefore, made in relation to the geometry in question (sheet, beam, bar, etc.)

If analytical models lend themselves well to simple structures, the same cannot be said for complex structures where discretization is unavoidable. The most commonly known is undoubtedly the finite element (FE) method that uses polynomial interpolation of elementary systems' deformations (such as bars, beams and plates). This interpolation is calculated using discrete values of displacements at specific nodal points in the structure to numerically solve partial derivative equations. As such, the FE method moves away from a continuous formation of the system's dynamic to a set of discrete differential equations described for specific degrees of freedom.

Constraints and deformation are related by the material's constituent relationships. For passive materials, the generalized Hooke law approximates this dependence in the context of linear elasticity. In the case of active materials, the Hook law must be completed or even substituted by the constituent law of the material in question in order to account for its mechanical properties and coupling (electrical, magnetic or thermal). In spite of the exception of some classes of material, such as electrostrictive materials or SMAs where strongly nonlinear behavior does not directly lend itself well to a formulation in a context of linear elasticity, piezoelectric, magnetostrictive or thermal expansion materials, for example, can be described by a set of linear constituent equations. Variational calculation (with the original intention of studying the dynamic behavior of purely mechanical structures) has proven a possible extension of active systems by taking into consideration energy in its different forms: elastic and electrical in the case of piezoelectric materials, for example. Couplings require the introduction of additional degrees of freedom within the system. In the majority of FE codes for piezoelectric materials, the electrical potentials for the nodes are considered [ALL 05]. When this is a question of materials sensitive to magnetic fields, we consider scalar magnetic potentials [MIF 06].

1.2.3.1. *Movement equations*

The application of these description formalisms obtains dynamic models in the form of matrix linear movement equations. They are of second order and involve radius K, mass M and damping D matrices, as follows:

$$M\ddot{p} + D\dot{p} + Kp = Fu \quad [1.1]$$

where Fu represents the influence of actuators on the flexible structure and the input u is the vector of external control values F defined by the distribution of the control governing the system. In the case of active elements within the structure, the degree of freedom vector p generally includes, in addition to nodal mechanical displacement, electrical or nodal magnetic potentials. Electromagnetic effects are generally characterized by dynamics which are significantly faster than those of a purely mechanical nature, to the extent that their contribution is essentially a quasi-instantaneous response. In this case, only the stiffness matrix expression is influenced by multiphysical coupling.

1.2.3.2. *Linear state-space representation*

With regard to the control, the linear movement equations are generally converted into the system's state equations. For purely mechanical problems, position and speed can define the state vector x and form the following state-space representation:

$$\dot{x} = \begin{bmatrix} \dot{p} \\ \ddot{p} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}D \end{bmatrix} \begin{bmatrix} p \\ \dot{p} \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1}F \end{bmatrix} u \qquad [1.2]$$

so that:

$$\dot{x} = Ax + Bu \qquad [1.3]$$

In the case of active closed-loop control systems, sensors are required to measure a variety of signals, such as displacements (capacitive sensors, lasers, etc.), forces or local deformations (deformation gauges, etc.). Linear measuring equations can therefore be modeled in the following general form:

$$y = Cx + Du \qquad [1.4]$$

where the vector y brings together all the outputs observed in the system. The matrices C and D are the observation and system transmission matrices.

The state model is therefore a function of the structure's essential characteristics (via stiffness, mass and system damping) as well as the influence of the distribution of actuators and sensors in the structure. In addition, the choice of these system inputs and outputs, that is a choice about the number, place and type of actuator and sensor, affects the performance, complexity and control of computational costs.

1.2.3.3. *Reduction of models*

The structural models obtained using FE methods involve a large number of degrees of freedom which are generally too numerous to be used in the design of control laws. Complex structures usually use several hundred or even thousand degrees of liberty, while corrector synthesis methods and their analytical tools only use models limited to tens of degrees of liberty. This disparity justifies the use of dynamic model reduction techniques which aim to limit the number of state vector components to consider the first vibratory modes influencing its response only [CRA 90].

1.2.3.4. *Controller synthesis*

The standard synthesis of a controller follows a sequential approach:

1) control objectives are specified to create a compromise between performance (settling time, precision, etc.) and regulation robustness (sensitivity, preventing disturbances, etc.);

2) exogenous variables and variables to be regulated are defined;

3) from the system's identified mode, the controller's structure is selected which is normally based on a preliminary selection of the system inputs (control values on the basis of which the controller reacts) and outputs (measured values from which the control law is calculated) and a choice of regulator synthesis (of which a number of methods exist) according to objectives, constraints on the regulator's implementation and the type of model;

4) after a validation stage in a simulation of the closed-loop system, the control law is implemented in the physical system.

Following the evaluation of the closed-loop system, iterations are possible in order to refine the controller's performance (Figure 1.10).

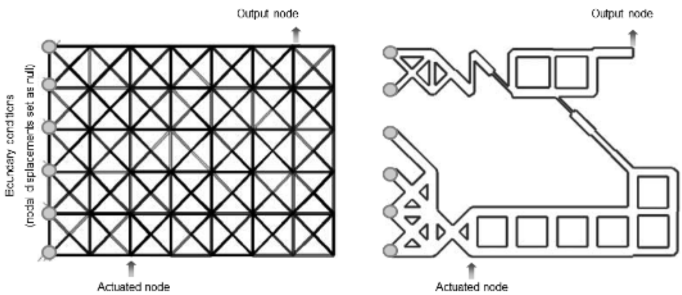
1.2.4. *Optimization strategies for micromechatronic structures*

The modelization, simulation and control of structures entail *a priori* parametrization of the problem (its topological domain, the structure's geometry, the materials used, etc.) on the basis of which optimization studies can be conducted to determine the best suited design for the structure, the choice of its materials, the implementation and physical integration of actuators and sensors, etc., in relation to the application's specification. We will now examine the different methods used in the optimal design of flexible structures used for robotic micromanipulation.

The majority of research into structural optimization entails optimizing the distribution of material in boundary conditions affecting the mechanism's motion and output. The objective is to obtain specific levels of performance and motion from this system. Optimization algorithms can be classified depending on their types. For example, determinist algorithms consider a convex, continuous and derivable search space, while stochastic optimization methods, such as evolutionary algorithms for simulated annealing-based algorithms, have the advantage of being able to consider a search space composed of discrete or even unvalued values. To find the optimal solution in terms of the criterion in question, stochastic methods cover the search space using a random exploration process based on the evaluation of this criterion for a large number of candidate solutions. They are in the order of 0 to the extent that they do not require a calculation of function–cost numerous times. In addition, no objective function, continuity property, nor function gradient is necessary. Their robustness and adaptability allow them to arrive at the numerical solution for otherwise difficult problems. However, it is their ability to function in non-standard search spaces which give them more potential. These methods lend themselves well to solving multi-objective optimization problems by creating a compromise between different criteria. Evolutionary algorithms [CHA 94], based on a simplified imitation of Darwinian population evolution as well as simulated annealing algorithms, are among the most commonly used non-determinist methods in structural topological optimization. However, this flexibility can be at the cost of computation time. The evaluation of objective functions and the exploration of the search space are two costly stages in terms of computation time. A solution to this problem involves using simple mechanical models such as bar or beam networks [SAX 02]. The use of beam flexion highlights the importance of their use in describing deformable mechanisms.

1.2.4.1. *Optimization of structural parameters*

This method, often qualified by "automatic structural sizing", aims to modify the straight section or transverse thickness of components in structures whose form and topology are fixed in advance. Beam models are frequently used to model deformable mechanisms. In this case, flexible transmission is simply viewed as a network of beams, which are cast and arranged according to a predefined model (Figure 1.16). A primary example of this is research such as that by [CAN 00] and [FRE 00] which examines the optimal synthesis of a deflection amplification mechanism in a piezoelectric actuator by considering the maximization of displacement of output as an objective function. Each beam in the network has a rectangular section that acts as an optimization variable. The lower limit of this rectangular section is deliberately low so that when elements reach this lower bound on the search space, they are ignored in the post-treatment phase. During the optimization phase, the remaining beam elements define the optimal topology.



a) b)

Figure 1.16. *a) Topological optimization domain and b) the optimal solution for the amplification of movement [CAN 00]*

It is also possible to define the characteristics of the external environment by specifying its stiffness. A range of research integrates these criteria affecting deformation energy [SAX 00] or maximizing mechanical advantage (ratio of force amplitudes generated between the mechanism's output and input) [KOT 99]. This method also exists in the case of bar arrangement which, in contrast to that of beams, is only solicited with traction/compression. The optimal size for multilayer mechanical structures has also been the subject of scientific studies. In the case of actuators and piezoelectric or magnetostrictive bimorphic sensors, optimizations directly affect the analysis of analytical models. The objective is, therefore, to maximize free deflection of the actuator's blocking force by varying specific parameters such as thickness of different layers of active and passive materials [GEH 00].

1.2.4.2. *Shape optimization*

This type of optimization method allows changes in shape that are compatible with a previously fixed topology. This approach, also known as an "sensitivity analysis" or "domain variation", relates to optimizing the position of a limited number of control points on the boundary. A slight variation in the shape of the boundary has a more or less significant effect on the value of the criterion being optimized. The analysis of variations along the domain's boundary for the values of the objective function enables the optimization process to iteratively improve an initial shape. This process is based on evaluating the gradient of the objective function in relation to optimization variables. Among the domain variation methods, the level set method (Figure 1.17) represents the boundary of the shape according to a level set function that has the advantage of being able to treat tridimensional and nonlinear elasticity problems [ALL 04, JOU 07]. These methods, however, can be costly in terms of calculation time depending on the initial form and its representation resolution. The resulting forms only vary according to their boundary that cannot modify the connectivity or nature of structural parts, i.e. to allow the appearance or disappearance of new edges or holes in the structure.

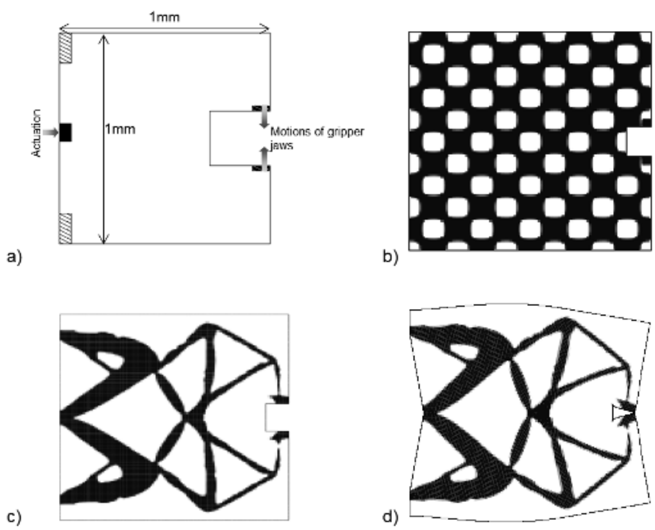


Figure 1.17. *Design of a 2D microgripper using the "Level-Set" method: a) definition of the problem, b) initial topology, c) optimal and d) deformed design [ALL 02]*

1.2.4.3. *Topological optimization*

Topological optimization aims to determine the nature of, and connectivity between, constituent elements in a structure. In this type of problem, only the boundary conditions and the spatial domain, in which it is possible to define the structure, are specified. This method, introduced by [BEN 88], generalizes the notion of shape, by moving away from the initial form. This method relies on the notion of a porous composite material. Variables of the topological optimization problem include the material's density at each point of the design process as well as the composite's mechanical properties. Homogenization theory relates to modeling the macroscopic behavior law using the porous microstructure characterized locally by the material's density, a continuous variable in the interval $[0, 1]$. Such densities are obtained by jointly considering a first material followed by a second which is characterized by a greater degree of flexibility. This formalism is mathematically necessary in order to obtain a well-posed problem and thereby ensure the existence of a solution.

In the practical field of microsystems, this optimization method has been exploited notably to design amplification structures for piezoelectric actuators whose movement is limited to several micrometer. The actuator is generally integrated into a passive structure whose optimal topology requires determination with regard to several criteria which could affect the maximization of the free movement of output when stationary [NIS 98] or at a specified frequency [SIL 99]. The geometric advantage of the structure (the ratio of displacements between the output and the input) can also be optimized according to other purposes such as designing inverse movement mechanisms (Figure 1.18).

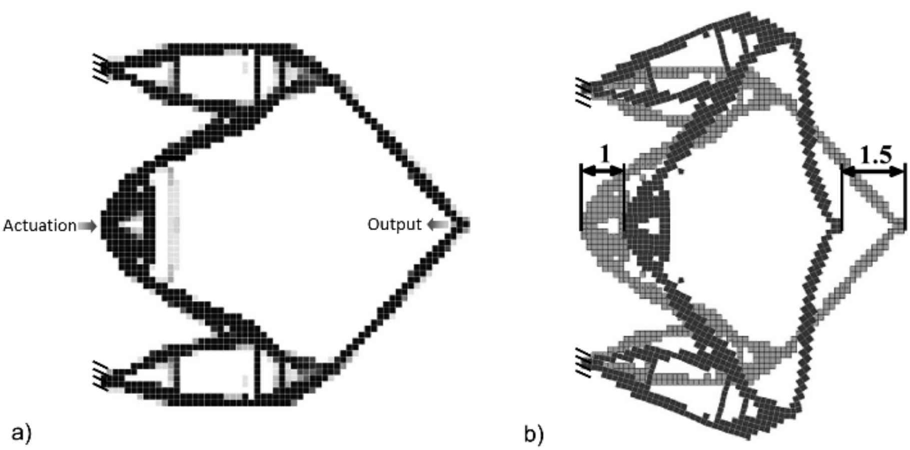


Figure 1.18. *a) An example reversing mechanism (geometric advantage* $\times 1.5$*) and b) a representation of its deformation [MIN 04]*

Integrated actuator micromechanisms are often still designed based on intuition and the designer's own experience, or using trial and error techniques. The extension of the homogenization method in the case of multiphysical problems, including phenomena such as piezoelectricity [TEL 90, GAL 92] or electromagnetism [YOO 00, YOO 04], have provided new perspectives in this field. Topological optimization of structures rendered active by the use of functional materials is therefore possible. A primary example of this includes study, such as research undertaken by Sigmund [SIG 98, SIG 01a, SIG 01b] and, more recently, research described in [RUB 06], which has introduced an optimal design aid method for monolithic planar microsystems with electrothermomechanical actuators. This method thereby achieves the perfect integration of the actuator function within the flexible mechanical structure. With a presumed weak electrothermomechanical coupling, three FE problems are solved sequentially. The analysis is first electrical, followed by a thermal and a final elastic analysis:

$$\begin{aligned} K_0 p_0 &= f_0 \quad \rightarrow \quad \text{Electrical analysis} \\ K_1 p_1 &= f_1\left(p_0\right) \quad \rightarrow \quad \text{Thermal analysis} \\ K_2 p_2 &= f_2\left(p_1\right) \quad \rightarrow \quad \text{Mechanical elasticity analysis} \end{aligned} \qquad [1.5]$$

where K_0 and K_1 are the global electrical conductivity and thermal global matrices, respectively, while K_2 is the mechanical stiffness matrix. p_0, p_1 and p_2 are the potential electrical, temperature and mechanical movement nodal vectors, respectively, while f_0, f_1 and f_2 are the electrical charge, thermal and mechanical nodal vectors, respectively. In the case of a material *continuum*, this method of topological optimization has been applied to designing a monolithic microgripper with a electrothermomechanical actuator (Figure 1.19).

1.3. Example of an optimal synthesis method for flexible piezoelectric transduction structures

This section introduces a preliminary design aid tool for mechanical deformation, actuator and distributed measuring structures. This method, developed by CEA LIST, is based on the optimal arrangement of basic flexible building blocks, such as beam-type systems, in a fixed design area.

We will illustrate several benefits of this method using several examples taken from mesoscopic scale robotic manipulation.

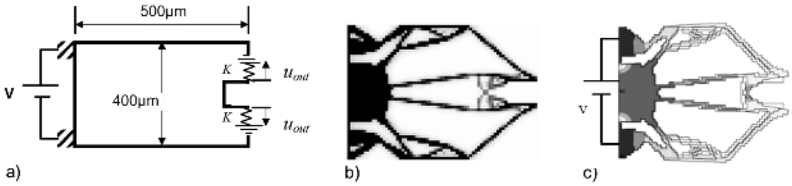


Figure 1.19. *Monolithic electrothermomechanical microgripper in nickel with an outer thickness of 15 μm: a) overload and boundary conditions, b) optimal solution and c) deformation [RUB 06]*

1.3.1. *Block method*

In the case of flexible structure composed of beams, it is generally possible to view its topology from the perspective of elementary flexible building blocks. To avoid considering all the combinations of possible beam arrangements, the mechanism is described using flexible building blocks of variable stiffness. These blocks are defined as predefined arrangements of several beams with a rectangular section within a given area (Figure 1.20). They are defined depending on the designer's experience and allow for future development of the method for taking into account new technological constraints of the problem. The blocks are also defined in order to avoid localized deformations. To accelerate the algorithm's convergence, each block (initially containing 13 nodes) is characterized by a rigidity matrix condensed on four external nodes in the block and calculated once for all at the start of the process. The FE method within a linear framework and with small perturbations on Navier-Bernoulli type beams in a rectangular section is used to calculate performance, presuming that the materials are linear elastic isotropes. Here, the block method examines the case of planar mechanisms. It uses an evolutionary algorithm inspired by [DEB 02], which enables multi-objective optimization. The size of the domain, the number of blocks to be used and the output points' characteristics (in relation to the target) are parameters fixed at the start of the process. The performance target is set by the user and the genetic algorithm evaluates the potential solutions using criteria such as modal controllability and observability[3]. The method enables the optimization of all or some of the variables defining the flexible structure: points adjoining the frame (fixed base), unilateral contacts (internal or external), distribution of actuators and other commonly used variables (topology–types of blocks and their arrangement–dimensions and material used). At the end of the optimization process, the method provides a list of the optimal flexible structures closest to that of the target which responds to the specification's constraints.

The distributed integration of actuator and measuring functions within a flexible structure is achieved by considering specific blocks of the library as active. These blocks with piezoelectric properties either result in a local deformation of the flexible structure due to the effect of an electrical field (actuator mode) or return information about deformations by generating electrical charges proportional to the deformation (sensor mode). The advantage of using active blocks is that they directly couple several degrees of mechanical freedom, thereby allowing complex movements within a single element in the flexible structure's meshing. This phenomenon has been highlighted in [GRO 07b] in relation to the design of a monolithic piezoelectric microactuator.

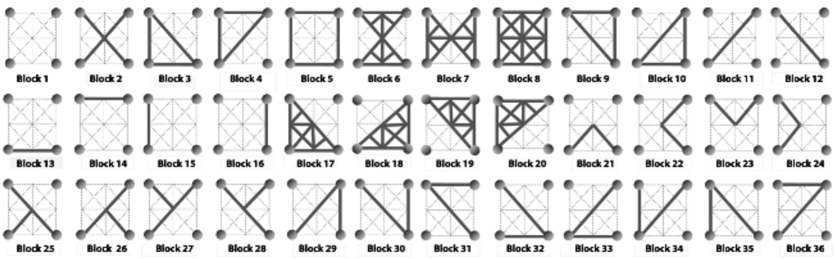


Figure 1.20. *The topologies of different elementary blocks in the library with their associated representative number*

1.3.2. *General design approach*

The optimal design method entails searching for an ideal distribution of authorized constituent blocks and the different structural parameters considered (Figure 1.21). The location of fixed nodes, the choice of material,

3 A definition will be introduced in Chapter 2.

the blocks' sizes and the location of active blocks in the structure can also be considered as optimization parameters. The algorithm is structured as follows:

– discrete parametrization of flexible mechanisms according to the design conditions (mesh size, topology, material and thickness and boundary conditions);

– stochastic operators for optimization (modification in the description of flexible mechanisms).

The genetic algorithm evaluates the criteria selected at each iteration and provides several pseudo-optimal solutions in the case of multicriteria optimization or a single solution for monocriterion optimization. The user interprets and analyzes the solutions to select solution according to the demands of the desired application.

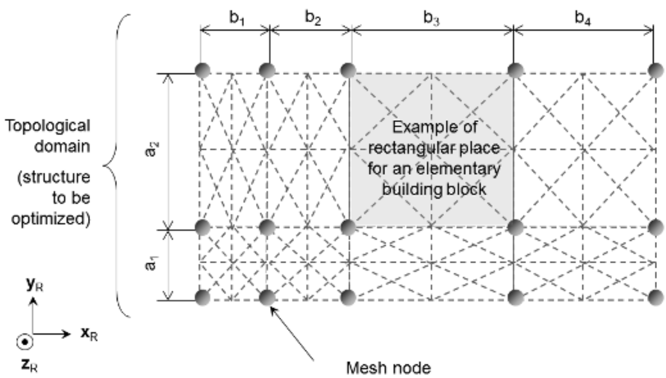


Figure 1.21. *Description of the mesh in the rectangular block framework*

1.3.3. *Finite element model*

The block models are obtained by considering an FE formulation of the Navier-Bernoulli type beams. The structural parameters of each rectangular block are their height, width and thickness. The material characteristics of each block are parametrized by the Young module, the Poisson coefficient, and the density and piezoelectric transduction coefficients. To calculate the different optimization criteria, the method uses the FE model from each block in the library. A model of the elementary piezoelectric beam must be developed beforehand by formulating the appropriate problem for these kinematic hypotheses [GRO 08, GRO 11].

From the linear equations defined by the piezoelectric standard [STD 96] and the generalized Hamilton principle for electromechanical systems [TIE 67], a variational approach is used to derive the formulation of the FE model for a piezoelectric beam. The detail of this calculation can be found in [GRO 08] and [ELK 10a]. The matricial expression of the elementary beam's dynamic behavior in its local position is formulated as follows:

$$M_p\ddot{X}_p + K_p X_p = G_p V_p + F_p \quad [1.6]$$

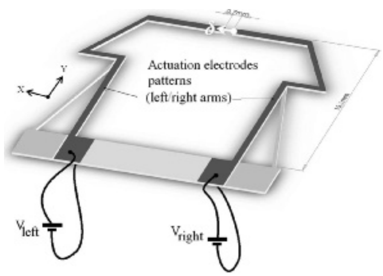
$$G_p^t X_p + C_p^t V_p = q_p \quad [1.7]$$

where M_p is the mass matrix, K_p the stiffness matrix, G_p the electromechanical coupling matrix, C_p the capacity matrix, X_p the nodal mechanical force vector and q_p the electrical charges distributed across the surface of the beam's electrodes. When the elementary beam is used in an actuator mode, the potential electrical signal applied to the surfaces of the electrodes induces movement of the nodes according to ratio [1.6]. At the same time, when the elementary beam is used in a sensor mode, the quantity of electrical charge received by the electrodes is in accordance with the deformation of the beam according to ratio [1.7]. In practice, the charge-tension converting electronic circuits use operational amplifiers which short circuit the upper and lower electrodes of the sensor beam, so that the measure ratio can be simplified as $q_p = G_p^t X_p$.

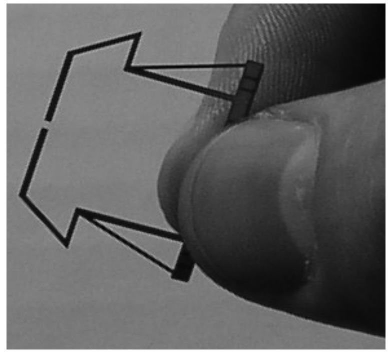
To consider the orientation of planar beams, the matrices of the FE model characterizing the electromechanical behavior of each beam are expressed generally and are then assembled to make up the matrices of each block and those of the overall flexible structure.

1.3.4. *Example applications: designing integrated flexible microgrippers*

The optimal synthesis method has been used to design piezoelectric monolithic microrobotic structures which can carry out the prehension function. It is composed of two fingered symmetrical clamping microgrippers with independent mobility. It may include structures integrating actuation (Figure 1.22) or even actuation and measuring (Figure 1.23).

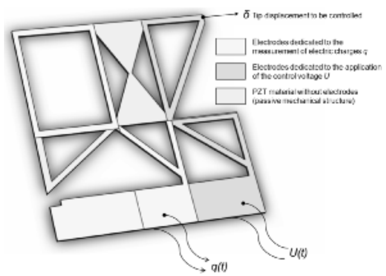


a)

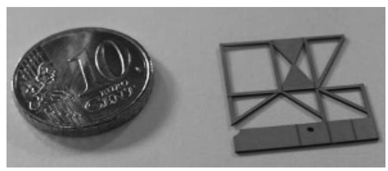


b)

Figure 1.22. *a) 3D view of the piezoelectric microgripper, the upper electrode path for the left and right fingers; b) photograph of the microgripper prototype manufactured using laser cutting. Free displacement of 10.69 µm and blocking force of 0.84 N for a potential electrical difference of 100 V [GRO 08]*



a)



b)

Figure 1.23. *a) 3D view of the left finger in a piezoelectric microgripper with its electrical actuator and measuring tracks; b) photograph of a prototype of the left finger in the microgripper manufactured using laser cutting. Free movement of 6.98 µm at the edge and charge in the order of 2×10^{-9}C for a difference in electrical potential of 100 V [EL 10]*

The structures shown in Figures 1.22 and 1.23 have been synthesized by considering various mechanical criteria (maximization of free output movement and blocking force maximization), measures (maximization of the quantity of charges generated by deforming the structure to use the electrical measure) and control (maximization of modal controllability and observability of dominant vibratory modes in the system's frequential response). In general, only the topology of an actuator finger is selected as an optimization parameter. The evaluation of method criteria is carried out when the system is subject to a difference in potential between the upper and lower electrodes in the active blocks. In contrast, the electromechanical properties of the passive blocks (not provided with electrical tension) are not used in this case. Only their mechanical criteria in terms of rigidity and mass affect the static and frequential behavior of the microstructure.

1.4. Conclusion

The demands related to the robotic manipulation tasks in the microworld direct the design of microgrippers toward the use of deformable mechanical structures. The structure's mechanical deformation, therefore, provides gains in positioning precision and can overcome some limitations related to polyarticulated mechanisms. In parallel, this general tendency means that these microsystems have a more significant functional density that gradually move closer to the adaptronic concept. The use of active materials plays an important role in these approaches. Indeed, where possible, the multifunctional material can simultaneously serve as a mechanical structure, actuator or even sensor. As a result, when designing these shapeable and integrated structures, the designer must carry out a multiphysical analysis of the problem that involves complex phenomena related to these particular structures.

New optimal synthesis methods for monolithic flexible structure have recently been developed. They optimally distribute and integrate actuator and measuring functions within the mechanical structure. This has been highlighted at the end of this chapter in relation to a topological optimization method. This is based on the optimal layout of elementary flexible blocks in order to synthesize piezoelectric transduction truss beam structures.

Approaches within optimal integrated structure design aim to consider:

– nonlinearities introduced via the behavior of active materials, particularly hysteresis phenomena in the case of piezoelectric transduction;

– the predictability of tridimensional effects (notably types of structural out-of-plane deformations);

– the synthesis of not only planar but also tridimensional mechanisms.

Finally, there are still far too few integrated structure optimization methods which consider optimal synthesis of control laws simultaneously with its mechanical design. This aspect will be the focus of the following chapter.

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