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Towards Medical Flexible Instruments: a Contribution to the Study of Flexible Fluidic Actuators

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At the end of this adventure, I leave with scientific knowledges, a better knowledge of me,

nice acquaintances and also new friends.

Abstract

The medical community has expressed a need for flexible medical instruments. Hence, this work investigates the possibility to use "flexible fluidic actuators" to develop such flexible instruments. These actuators are driven by fluid, i.e. gas or liquid, and present a flexible structure, i.e. an elastically deformable and/or inflatable structure.
Different aspects of the study of these actuators have been tackled in the present work:

- A literature review of these actuators has been established. It has allowed to identify the different types of motion that these actuators can develop as well as the design principles underlying. This review can help to develop flexible instruments based on flexible fluidic actuators.

- A test bench has been developed to characterize the flexible fluidic actuators.

- A interesting measuring concept has been implemented and experimentally validated on a specific flexible fluidic actuator (the "Pneumatic Balloon Actuator", PBA). According to this principle, the measurements of the pressure and of the volume of fluid supplied to the actuator allow to determine the displacement of the actuator and the force it develops. This means being able to determine the displacement of a flexible fluidic actuator and the force it develops without using a displacement sensor or a force sensor. This principle is interesting for medical applications inside the human body, for which measuring the force applied by the organs to the surgical tools remains a problem.
  The study of this principle paves the way for a lot of future works such as the implementation and the testing of this principle on more complex structures or in a control loop in order to control the displacement of the actuator (or the force it develops) without using a displacement or a force sensor.

- A 2D-model of the PBA has been established and has helped to better understand the physics underlying the behaviour of this actuator.

- A miniaturization work has been performed on a particular kind of flexible fluidic actuator: the Pleated Pneumatic Artificial Muscle (PPAM). This miniaturization study has been made on this type of actuator because, according to theoretical models, miniaturized PPAMs, whose dimensions are small enough to be inserted into MIS medical instruments, could be able to develop the forces required to allow the instruments to perform most surgical actions. The achieved miniaturized muscles have a design similar to that of the third generation PPAMs developed at the VUB and present a total length of about 90 mm and an outer diameter at rest of about 15 mm. One of the developed miniaturized PPAMs has been pressurized at $p = 1$ bar and it was able to develop a pulling force $F = 100$ N while producing a contraction $\epsilon = 4$ %.
  Propositions have been made regarding a further miniaturization of the muscles.

Contents

Chapter 1

Introduction

1.1 Context of the research

Flexible instruments, i.e. instruments presenting a large number of degrees of freedom (DOFs) and able to perform snake-like movements when avoiding obstacles, can find a lot of applications in the medical field and the three following examples will bring this to light.

1. During a Minimally Invasive surgery (MIS) procedure, only a few small incisions are performed in the patient's body to insert the surgical tools and a camera for visualization. The tools manipulated by the surgeons are rigid rods, presenting four DOFs (see Fig. 1.1), sliding in trocars (which are used to keep the incisions open) and whose tips are analogous to the instruments used in open surgery [68].
   Robotically-assisted systems for MIS (such as the Zeus system or the da Vinci system) have been commercially available for about ten years. Compared to traditional MIS, the rigid rods are equipped with articulated wrists placed at their tips and which present up to two DOFs. These robotically-assisted systems brought about a lot of advantages to MIS such as a more comfortable settling of the surgeon during the operation and an improved motion precision thanks to tremor filtering and motion scaling [33].
   Nonetheless, some drawbacks remain in chest surgery such as a limited dexterity and working space. Due to these two inconveniences, the insertion points sometimes need to be replaced during the operation, to allow the surgeons to do the necessary movements and to reach the target points [68]. In [33], a surgeon trained with the Zeus system explains that this is due to the rigid rods passing between the ribs and he proposes to develop flexible instruments. In addition to this opinion, [68] gathers the views of other surgeons and engineers about the shortcomings of the existing surgical robots (notably the da Vinci system) and underlines a need for instruments presenting high mobility.

2. In the field of endoluminal surgery, where the surgical tools pass through natural orifices, a need for flexible tools is also expressed by the medical community [4].

3. Concerning catheters, which are flexible tubes inserted into vessels, [45] mentioned the need for active catheters, i.e. actuated catheters able to move their shaft, to ease their insertion. Indeed, the insertion of classical passive catheters is difficult due to the small diameter of the vessels and their complex shape (with bending, twisting and branching).

For MIS applications, instruments must have a diameter less than 10 mm [65] while the diameter of catheters can be as low as 1 mm or less [59]. Developing flexible instruments for medical applications is thus a miniaturization challenge.

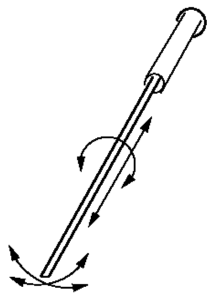


Figure 1.1: Four DOFs in Minimally Invasive Surgery: one translation, one axial rotation and two rotations around the insertion point. Figure adapted from [28].

1.2 Flexible Fluidic Actuators and aim of the thesis

"Flexible Fluidic Actuators" is the name we decided to give to actuators driven by fluid, i.e. gas or liquid, and presenting a flexible structure, i.e. an elastically deformable and/or inflatable structure. As will be shown later in more details, such actuators present interesting features regarding medical applications. Hence, the aim of the thesis is to study these actuators and to investigate whether it is interesting to use them to develop flexible instruments for medical applications.

1.3 Content and contributions of the thesis

Chapter 2 allows to become familiar with the flexible fluidic actuators. It lists the advantages and drawbacks linked to the use of these actuators, discusses about the miniaturization of the periapherics of these actuators and presents a literature review of these actuators. This review has been published (see [40]) and is the first contribution of the thesis. It shows the different design principles of these actuators and it sorts them according to their ability to stretch themselves or shorten, bend themselves or rotate. Hence, this review can help to design medical flexible instruments based on flexible fluidic actuators.

Among the interesting features linked to the use of flexible fluidic actuators, one has caught our eye. Indeed, in [78], a flexible fluidic actuator, called "the Flexible Microactuator", is presented and it is suggested that the measurements of the fluid pressure and of the volume of supplied fluid allow to determine and control the position of the actuator and the force it develops. This property, that will hereafter be referred to as the "Pressure-Volume-Force-Position principle" or "PVFP principle", means being able to determine the displacement of a flexible fluidic actuator and the force it develops without using a displacement sensor or a force sensor [78]. The PVFP principle is schematically presented in Fig. 1.2. According to us, this measuring principle can be applied to all flexible fluidic actuators whatever the actuation fluid (compressible or incompressible).
To study and implement the PVFP principle, a flexible fluidic actuator called "Pneumatic Balloon Actuator" (PBA) has been used. This actuator, invented by [49], has been selected among the actuators of the review because it has a simple design, one DOF and because it is easily manufactured. An example of such an actuator is presented in Fig. 1.3. A PBA is composed of two square layers whose materials have different rigidities, the upper layer being less rigid than the lower one. Both layers are fixed to each other along their surrounding edge and this forms a square cavity. The actuator is fixed as a cantilever and when the cavity is pressurized, the actuator free end moves upwards.

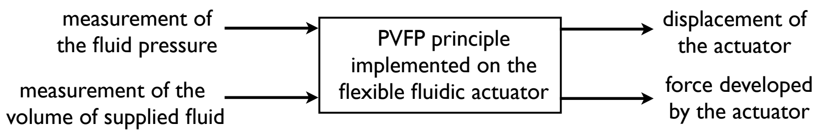


Figure 1.2: Schematic representation of the PVFP principle: according to this principle, the measurements of the fluid pressure and of the volume of supplied fluid allow to determine and control the position of the actuator and the force it develops.

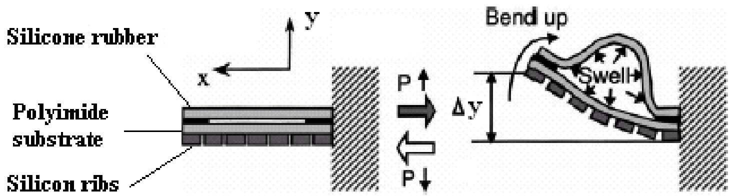


Figure 1.3: Working principle of a Pneumatic Balloon Actuator (PBA): PBA at rest and pressurized PBA on the left hand side and the right hand side, respectively.

Fig. 1.4 presents a PBA linked to a syringe-pump; the actuation fluid is air. The volume of fluid supplied to the actuator is considered to be the volume swept by the piston during its displacement; this swept volume is proportional to the piston displacement u and equals Su, where S is the syringe-pump cross-section. Therefore, the piston displacement u will be used for the PVFP principle rather than the swept volume.
When a displacement u is imposed to the piston, the inner pressure p_{in} increases and the PBA inflates and its free end A moves upwards. The vertical and horizontal displacements of this point are Δy_0 and Δx_0, respectively. Afterwards, keeping the piston position constant, if a weight w is hung from the PBA free end, the inner pressure p_{in} increases and the displacements Δy and Δx of the PBA free end decrease. According to the PVFP principle, knowing the values of p_{in} and u allows to determine the displacements of point A and the value of the weight w.

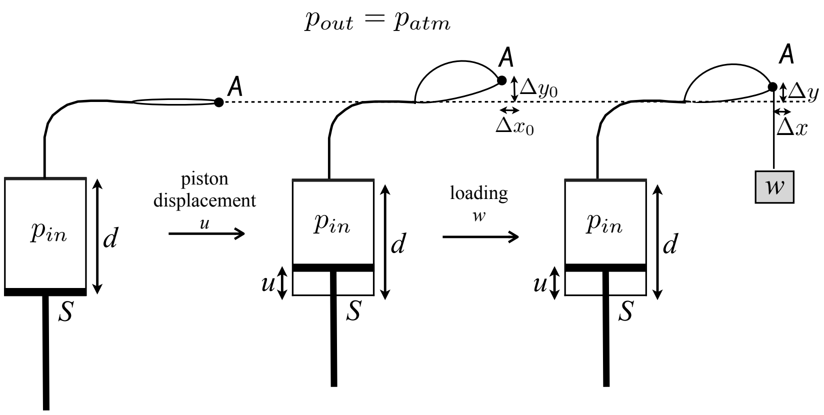


Figure 1.4: Pneumatic Balloon Actuator (PBA) linked to a syringe-pump.

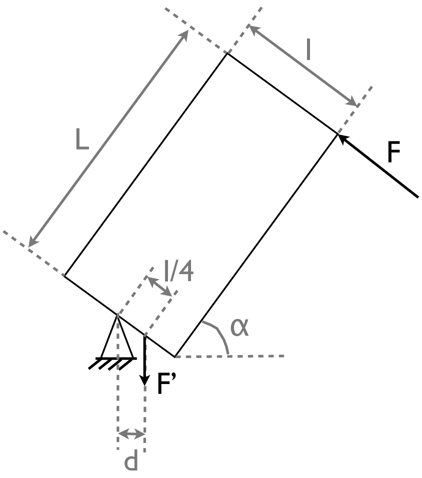
PBAs have been manufactured and the PVFP principle has been successfully implemented on a PBA. To do so, experimental models of the behaviour of the PBA have been established and then used to predict the actuator displacements Δx and Δy and the load w attached from its end, on the basis of the measurements of u and p_{in}. This experimental validation of the PVFP principle on a PBA constitutes the second contribution of the thesis and it is presented in Chapter 5 as well as a discussion about the practical implementation of the PVFP principle in a targeted application.
The PVFP principle is an interesting measuring concept for applications where the space is limited and where a miniaturization effort is required. This is for example the case in Teleoperated MIS where it is necessary to measure the force applied by the tools to the organs to ensure a force feedback of good quality. Obtaining this measurement is not straightforward. Indeed, if the force sensor is placed on the tool, outside the body of the patient, the measurement will be polluted by the friction of the trocar. To solve this problem, some researchers propose to place the sensor at the end of the tool inside the body but this raises the challenge to develop a small and sterilizable force sensor [63]. Using flexible fluidic actuators to actuate the surgical tools and exploiting the PVFP principle would allow to measure the force applied to the organs without the need for a force sensor. Besides, the measurements of the fluid pressure and of the volume of supplied fluid could be performed outside the patient's body.

A 2D-model of the PBA is presented in Chapter 6; it has been built in order to better understand the physics underlying the behaviour of this actuator. The results provided by this model have been compared with the measurements performed on two PBAs. Because of the numerous assumptions on which the model rests, its quantitative results are far from the measurements performed on the prototypes and other comparisons with experimental results are needed to assess whether the qualitative results provided by the model are correct. However, this model is able to predict the bidirectional behaviour that has been experimentally noticed by different researchers on PBAs made of only one material (the upper membrane being thinner than the lower one). A PBA presenting a bidirectional behaviour moves its end upwards when it is pressurized until a given pressure level is reached and above this level, the PBA tip is moved downwards.
This model constitutes the third contribution of this thesis.

A literature review (see Table 1.1) has established that a force of about 13 N is required at the end of a surgical instrument to allow the execution of all the surgical gestures. Fig. 1.5 presents schematically a surgical instrument having a length L and a width l. F is the force applied by the organs to the tip of the surgical instrument. An actuator applies a vertical force F' to the basis of the instrument and α is the angle of inclination of the instrument. For $L = 2l$, if α equals $\pi/2$, the actuator has to develop a force $F' = 104$ N so that the instrument can develop a force $F = 13$ N at its tip. On the other hand, if α equals $\pi/6$, the actuator has to develop a force $F' = 208$ N so that the instrument can develop a force $F = 13$ N at its tip. According to theoretical models, a miniaturized Pleated Pneumatic Artificial Muscle (PPAM, see Fig. 1.6), whose dimensions are small enough to be inserted into a MIS medical instrument, could able to develop the required force of 104-208 N. Therefore, the PPAMs have been studied in order to assess their miniaturization potential. The fourth contribution of the thesis is the miniaturization work done on the PPAM, in collaboration with the Vrije Universiteit Brussel (VUB) which has developed this actuator; this is presented in Chapter 7. The achieved miniaturized muscles have a design similar to that of the third generation PPAMs developed at the VUB and present a total length of about 90 mm and an outer diameter at rest of about 15 mm. One of the miniaturized PPAMs has been pressurized at $p = 1$ bar and it was able to develop a pulling force $F = 100$ N while producing a contraction $\epsilon = 4$ %.

Source	Action	Organ	Force measurement
[36]	Piercing	Sheep heart	Max force: 0.3 N
[63]	Suturing	Rat: skin, muscle and liver tissue	Max force: 2.3 N
[82]	MIS actions: Cutting, suturing dissecting, biopsy by traction, knotting, palpation, prehension	Pelvi-trainer (in vitro), pig, human (coelioscopy, thoracoscopy)	Force range: 0.48 N to 12.86 N
[57]	Various MIS interventional tasks	Various	Force range: 0.1 N to 3 N

Table 1.1: Forces measured at the tip of the surgical tools during the execution of different surgical gestures. For source [82], the minimum value of the force range has been computed, by a torque equilibrium, from the measurement of the force applied to the handle of the tool; the maximum value of the force range is the difference between the force applied to the handle of the tool (14.34 N) and the friction in the trochar (1.48 N).



$$F'.d = F.L$$

with $d = \frac{l}{4} sin(\alpha)$

$$\boxed{F' = F\frac{4L}{l.sin(\alpha)}}$$

For $L = 2.l$ and $F = 13\ N$

1) $\alpha = \pi/2$

$$\boxed{F' = 104\ N}$$

2) $\alpha = \pi/6$

$$\boxed{F' = 208\ N}$$

Figure 1.5: The surgical instrument has a length L and a width l. F is the force applied by the organs to the tip of the surgical instrument. An actuator applies a vertical force F' to the basis of the instrument. α is the angle of inclination of the instrument. For $L = 2l$, if α equals $\pi/2$, the actuator has to develop a force $F' = 104$ N so that the instrument can develop a force $F = 13$ N at its tip. On the other hand, if α equals $\pi/6$, the actuator has to develop a force $F' = 208$ N so that the instrument can develop a force $F = 13$ N at its tip.

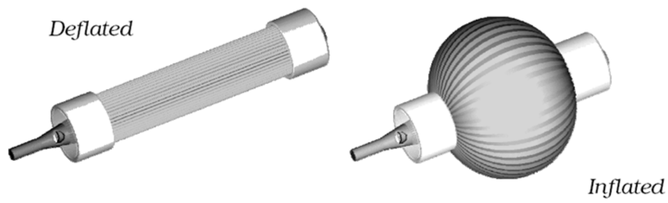


Figure 1.6: Deflated and inflated states of a PPAM. When pressurized gas is introduced in this actuator, the membrane bulges out and contracts axially. Figure from [83].

To study the PVFP principle and to characterize the PBAs and the miniaturized PPAMs, a test bench has been developed. It constitutes the fifth contribution of this thesis and its design and building are described in Chapter 3. This test bench is basically a syringe-pump composed of a linear motor linked to a cylinder and the output of the cylinder is linked to the actuator to be studied by a tube. When the motor moves the cylinder piston, the fluid located in the cylinder chamber and the tubes is compressed and the flexible fluidic actuator is pressurized.

Finally Chapter 8 presents the conclusions of the thesis and the perspectives for future works.

1.4 Reading suggestion

The reader in a hurry can get the gist of this work by reading the following parts:

- Chapter 2 "Flexible fluidic actuators":
  - Advantages and drawbacks of flexible fluidic actuators: Section 2.2
  - Miniaturization of fluidic actuators peripherics: Section 2.3
  - Literature review of the flexible fluidic actuators: the introduction (Section 2.4.1), the general descriptions of the different categories of flexible fluidic actuators (the first pages of Sections 2.4.2, 2.4.3, 2.4.4 and 2.4.5) and the conclusion (Section 2.5).
- Chapter 3 "Test bench":
  - Description of the test bench: Section 3.5
  - Conclusions: Section 3.6
- Chapter 4 "Study of the PVFP principle and of the Pneumatic Balloon Actuators: Test bench particularities"
- Chapter 5 "The PVFP principle"
- Chapter 6 "Model of the Pneumatic Balloon Actuator"
- Chapter 7 "Miniaturization of Pleated Pneumatic Artificial Muscles"
- Chapter 8 "Conclusions and perspectives"

Chapter 2

Flexible fluidic actuators

2.1 Introduction

The aim of this chapter is to get familiar with the flexible fluidic actuators. These actuators are driven by fluid, i.e. gas or liquid, and present a flexible structure, i.e. an elastically deformable and inflatable structure.
Section 2.2 lists the advantages and difficulties linked to the use of these actuators while Section 2.3 discusses about the miniaturization of their peripherics (such as the valves and the flow control devices). Indeed, according to the application targeted for the flexible fluidic actuators, some miniaturization might be necessary and miniaturizing the actuators means also miniaturizing their peripherics.
Section 2.4 presents a literature review of these actuators. The goal of this review is to help to develop medical flexible instruments based on flexible fluidic actuators. Therefore, the review identifies the movement types that these actuators can generate and the design principles underlying. Hence, it presents the working principle of each actuator and also focuses on other characteristics such as the DOFs, the materials, the manufacturing process, the actuator dimensions, the actuation mode (pneumatic or hydraulic), the pressure range and the performance in terms of developed force and displacement.
Finally, conclusions are presented in Section 2.5.

2.2 Advantages and drawbacks of the flexible fluidic actuators

The fluidic actuation presents nice features regarding an application inside the human body. Indeed, it has the non-negligible advantage to prevent having energized parts, i.e. under electrical voltage, (unlike the electrostatic actuators, the piezoelectric actuators [81], the Electroactive Polymers or the electromagnetic motors when used inside the body) or high temperature parts (unlike the Shape Memory Alloys and thermal actuators) inside a patient's body; this increases the safety. As no electrical power is used, operation in presence of radioactivity or magnetic field is possible [25]. In the case of a hydraulic actuation, a sterile physiological saline solution could be used so that a leakage of the system would have no consequence on the patient's body.
One can think of miniaturizing classical piston-based fluidic actuators but it raises difficulties regarding the sealing of the chambers. O-rings and lip seals are no longer suitable [34] because small variations of the shape or size of the components (seal, seal house or piston) involve high friction or leakage. [34] proposes to use "restriction seals", i.e. small clearances between the rod and the orifice. These generate less friction and allow a compromise between the

leakage and the manufacturing accuracy; the actuator can present virtually no leakage but then tolerances in the range of 1 μm or less are required. However, to avoid leakages and friction which limit efficiency, we chose to use pressurized elastic deformable chambers, i.e. flexible fluidic actuators, as suggested by [78].
As these actuators present no relative motion of parts, static sealings can be used and this means no need for lubricants, no leakages and no wear particles; consequently these actuators could possibly operate in clean room, food or agriculture industries [25]. Besides, smooth motion and precise positioning are possible to achieve since there is no friction [78] (unlike piston-based actuators or systems actuated with cables). In the field of robotics, compliant structures have relevant additional advantages over traditional rigid body robots:

- They can handle delicate objects without causing any damage thanks to their own compliance [25]. This compliance allows them to adapt themselves to their environment during contacts [25] [66].

- Compared to traditional mechanisms made of articulated rigid parts, compliant structures allow the reduction of the number of parts necessary to perform a given task [44]. This is an interesting feature regarding miniaturization.

- When they are made of membranes, flexible structures can be very lightweight. If the instrument is actuated thanks to inflatable membranes, its volume may be reduced when the membranes are deflated. This is an interesting characteristic if the whole device has to be inserted into a small orifice.

The combination of a fluidic actuation and a flexible structure also brings advantageous properties:

- Regarding a medical application, reducing the fluid pressure lets the device loose its rigidity and lets it regain its initial shape. In emergency cases, it then allows to take the instrument out of the patient's body quickly.

- Concerning the "Flexible Microactuator" (FMA, see section 2.4.2) whose actuation is obtained by the deformation of elastic chambers, [78] said that "*By measuring the volume and pressure of an operating fluid having been supplied, the operator can learn about the posture of the actuator and the acting force; that is, it is possible to control the posture and the acting force without equipping a sensor on the distal end of the actuator.*" This remark seems to be applicable to all devices based on the same actuation principle.

Nevertheless, a fluidic actuation presents some drawbacks:

- It needs equipment such as pumps, valves and pipes that can be bulky. However, in the case of a medical application, the pump is placed outside the patient's body and will not increase the bulkiness of the instrument inside the body.

- Regarding fluidic micro-actuators, [23] mentioned different drawbacks: the pipes used to drive the fluid can present leakages and cause pressure losses which limit efficiency. Moreover, controlling pressures and debits in small sections is often more delicate than controlling electrical quantities.

- Still, an important shortcoming of flexible fluidic actuators lies in their control strategy, as explained by [25]: "*Fluidic flexible robots require sophisticated controls in order to reach accurate and repeatable positioning. Further their dynamics modeling has to fight with the deformable structure and with not conventional actuations.*"

Comparing liquids and gases, one can note that the compressibility of gases brings more compliance, leads to a more difficult study and involves thermal losses upon compression. Air is a readily available source and exhaust gases can be freely evacuated in the ambient air [70]. Finally, gases lead to more lightweight actuators and to pressure losses a hundred times smaller than for liquids [79].

2.3 Miniaturization of fluidic actuators peripherics

Regarding the miniaturization of the actuators, [70] explains that the size of the valves and of the flow control devices needs to be correspondingly reduced as the scale decreases. To answer this need, the Lee company [6] provides miniature fluidic equipments and custom miniature valves can be found in the literature, as people developing micro flexible fluidic actuators sometimes develop their own miniature valves (for example [67] and [45]). Besides, as thermal time constants decrease nicely when the scale decreases, thermo-pneumatically controlled valves can be used, in pneumatic systems, at the meso- and micro-scales [70].

2.4 Literature review of the flexible fluidic actuators

2.4.1 Introduction

This section proposes a review of the flexible fluidic actuators found in the literature. The goal of this review is to help to develop medical flexible instruments based on flexible fluidic actuators. Therefore, this review identifies the movement types that these actuators can generate and the design principles underlying. The working principle of each actuator as well as some applications are presented and the review also focuses on other characteristics such as the DOFs, the materials, the manufacturing process, the actuator dimensions, the actuation mode (pneumatic or hydraulic), the pressure range and the performance in terms of developed force and displacement. Tables 2.1 and 2.2 summary the characteristics of many actuators described in this review.
At the light of this review, it has been established that the flexible fluidic actuators can bend themselves, stretch themselves, shorten or develop a rotational motion and some of them present several DOFs. The review sorts the actuators in three categories according to their bending, rotation or stretching/shortening ability. Two different methods to achieve bending have been identified and will be described in more details later. The first technique is based on "internal chambers differently pressurized" and the other one on "anisotropic rigidity". Besides, two methods to generate a rotational motion have also been identified. The actuators based on the first technique present a structure reinforced in places (with fibres or by increasing the material thickness) in such a way that when the actuators are pressurized, their structure involves a rotation. The second method to generate a rotational motion consists in an articulated structure in which one or several flexible fluidic actuators are inserted. When the actuators are pressurized, they actuate the structure which involves a rotation.
The classification of the flexible fluidic actuators, according to the movement types they can generate, is schematically presented in Fig. 2.1.

2.4.2 Bending thanks to internal chambers differently pressurized

The devices based on this principle will hereafter be referred to as "chambers actuators". They present elongated chambers placed between two plates and the chambers are designed in such a way that when they are pressurized, their length increases or decreases. Hence, when a chamber is pressurized, its length changes while the other chambers keep their initial

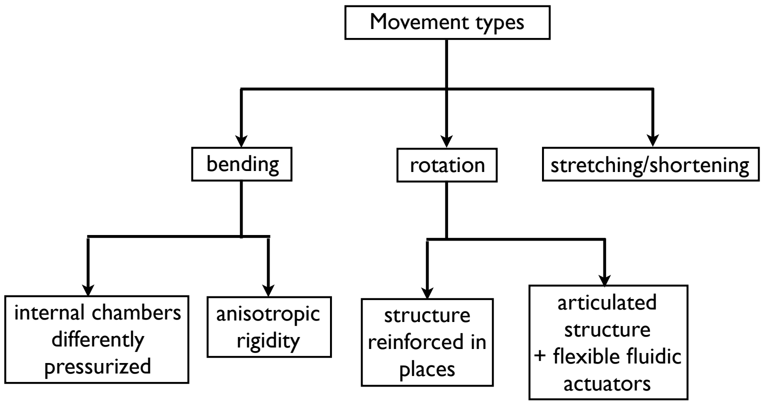


Figure 2.1: Classification of the flexible fluidic actuators according to the movement types they can generate.

length and consequently the whole device bends. According to the type of actuator, the bulging of the chambers may be hampered.
Fig. 2.2 presents a chambers actuator having three chambers and the chambers are such that they stretch themselves when they are pressurized. Hence, if chamber no. 1 is pressurized, its length increases and the device bends as shown in the figure.

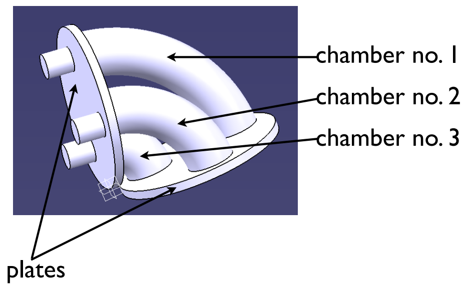


Figure 2.2: Chambers actuator presenting three elongated chambers placed between two plates. The chambers are designed in such a way that their length increases when they are pressurized. Hence, if chamber no. 1 is pressurized, its length increases while the other chambers keep their initial length and consequently the whole device bends as shown in the figure.

The chambers can be of different types (see Fig. 2.3 and 2.4):

- bellows which expand when pressurized (see no. 1 in Fig. 2.3).
  For example, a chambers actuator based on bellows has been used in a coloscope [81], a "Dextrous Underwater Manipulator" [61] and a catheter or endoscope [46].

- pneumatic artificial muscles which contract when pressurized (see no. 2 in Fig. 2.3).
  For example, a chambers actuator based on McKibben pneumatic artificial muscles has been used in the "Octarm" [56] which is a continuum manipulator.

- elastic tubes with mechanical constraints (see no. 3 in Fig. 2.3). The mechanical constraints are obtained thanks to fibres fixed to the tubes and according to the type

of mechanical constraints, the elastic tube will shorten, stretch itself, bend itself or develop a torsion motion.
For example, a chambers actuator based on such elastic tubes is used in [43] and [84].

- microballoons (see no. 4 in Fig. 2.3).
  A chambers actuator based on microballoons has been used in a positioning system for a catheter [67] (see the figure illustrating no. 4 in Fig. 2.3). The balloons are pressed against the vessel walls and this allows to fix the catheter tip at a certain place in the vessel. After this is achieved, changing the balloon's size enables to change the orientation of the catheter tip.

- flexible and extensible tubes fixed to a core member (see no. 5 in Fig. 2.4).
  Such a chambers actuator is presented in [58]. The core member is made of a flexible but inextensible material. The tubes are designed in such a way that when pressurized, they will extend axially but will not bulge radially. When the pressure is increased in one tube, the other tubes keep their initial length while the core member is not able to lengthen and it causes the bending of the device. Three designs A, B and C are shown in the figure illustrating no. 5 in Fig. 2.4; they are composed of one, two and three tubes, respectively.

- internal chambers in a tube (see no. 6 in Fig. 2.4). These chambers are designed in such a way that they stretch themselves when they are pressurized.
  For example, the "Flexible Microactuator" of [72] presents such chambers and it will be described in more details later.

- balloons in a bellows tube (see no. 7 in Fig. 2.4). When they are pressurized, these balloons stretch themselves.
  For example, the "Fluidic Bellows Manipulator" of [25] presents such chambers and it will be described in more details later.

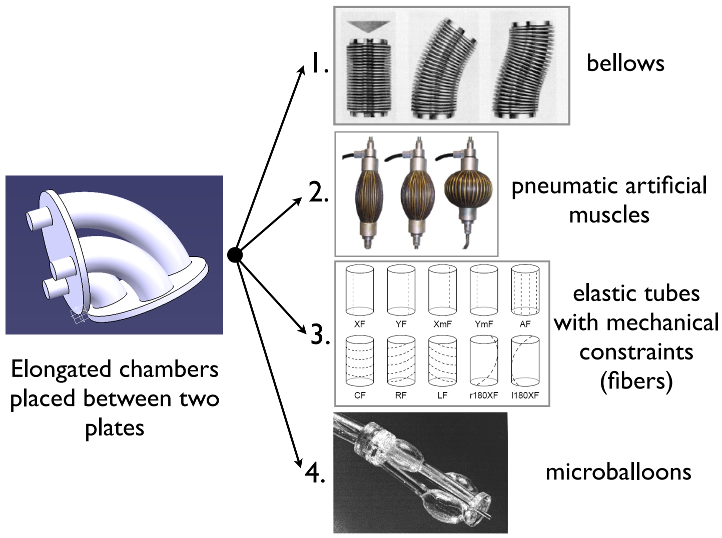


Figure 2.3: "Chambers actuators": they present elongated chambers placed between two plates and the chambers are designed in such a way that when they are pressurized, their length increases or decreases. Hence, when a chamber is pressurized, its length changes while the other chambers keep their initial length and consequently the whole device bends. These chambers can be of different types such as bellows (figure from [66]), pneumatic artificial muscles (figure from [26]), elastic tubes with mechanical constraints (figure from [43]) or microballoons (figure from [67]).

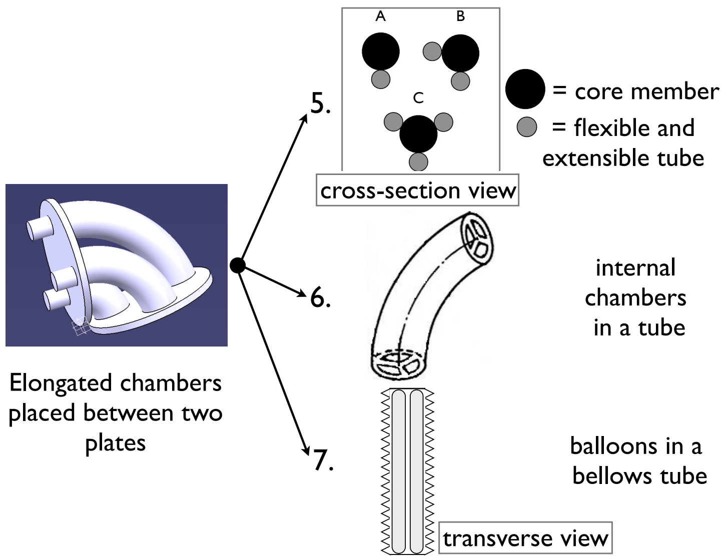


Figure 2.4: "Chambers actuators": they present elongated chambers placed between two plates and the chambers are designed in such a way that when they are pressurized, their length increases or decreases. Hence, when a chamber is pressurized, its length changes while the other chambers keep their initial length and consequently the whole device bends. These chambers can be of different types such as flexible and extensible tubes fixed to a core member (figure reproduced from [58]), internal chambers in a tube (figure adapted from [72]) or balloons in a bellows tube.

A) Example of a chambers actuator presenting internal chambers in a tube: the "Flexible Microactuator" (FMA)

In [72], [73], [74] and [71], K. Suzumori et al. describe the "Flexible Microactuator" (FMA), which is a pneumatic rubber actuator. It is a cylinder presenting three internal chambers and it is composed of silicone rubber reinforced with nylon fibres disposed in a circular direction (see Fig. 2.5). The function of these fibres is to create anisotropic elasticity in order to prevent radial deformations. When a chamber is pressurized, its length increases while the other chambers keep their initial length and consequently the cylinder bends in the direction opposite the pressurized chamber. For example, Fig. 2.6 presents a bending FMA whose chambers no. 1 and 2 are pressurized.

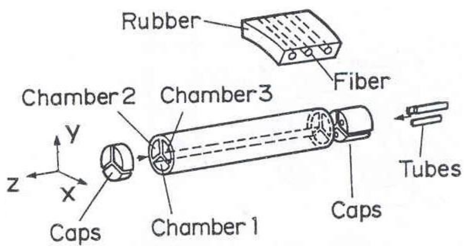


Figure 2.5: Parts of a Flexible Microactuator (FMA): it is a cylinder presenting three internal chambers and it is composed of silicone rubber reinforced with nylon fibres disposed in a circular direction. The function of these fibres is to create anisotropic elasticity in order to prevent radial deformations. Figure from [72].

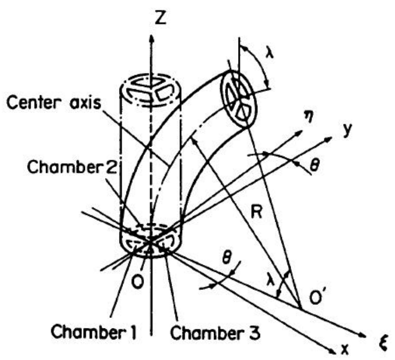


Figure 2.6: Bending Flexible Microactuator (FMA): when a chamber is pressurized, its length increases while the other chambers keep their initial length and consequently the cylinder bends in the direction opposite the pressurized chamber. The figure presents a bending FMA whose chambers no. 1 and 2 are pressurized. Figure from [72].

An electro-pneumatic (or electro-hydraulic) system is used to control the motion of the FMA and it enables to control the pressure in the chambers independently. This system comprises flexible tubes connected to the chambers and to pressure control valves.
The FMA is said to bend in any direction thanks to appropriate pressures in the chambers. Besides, it can stretch in the axial direction when the pressure is equally increased in all the chambers. Hence, an FMA has three DOFs (one stretching and two bending DOFs).
Several FMAs can be connected in series to increase the number of DOFs and FMAs have

been used to build a multi-fingered robot hand, walking robots, pipeline inspection robots, etc.
The FMAs reinforced with fibres are obtained from liquid silicone rubber and nylon fibres, by a moulding process. The small dies used for this operation are made using an electrical discharge machining process [73].
In [75] and [76], the authors wanted to miniaturize and integrate FMAs. To achieve this, the moulding process was no longer suitable and stereo-lithography was preferred. Since a product produced by stereo-lithography must be made of a single material, a new design has been developed to obtain anisotropic elasticity without fibres. This has been achieved thanks to "restraint beams" (see Fig. 2.7). These are rubber walls added to the FMA chambers to prevent the radial deformation of the actuator.

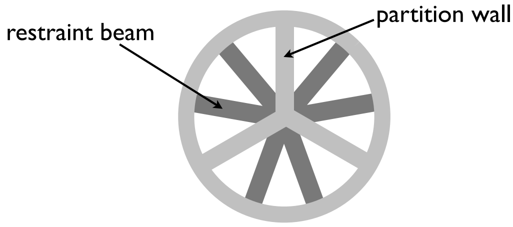


Figure 2.7: Cross-section view of a Flexible Microactuator (FMA) with two "restraint beams" in each chamber: the restraint beams are rubber walls added to the FMA chambers to prevent the radial deformation of the actuator. Hence, they allow the manufacturing of a fibreless FMA made of only one material, which can thus be processed by stereo-lithography. Figure redrawn from [75].

Another FMA fibreless design is presented in [77]. The cross-section of this FMA presents three chambers (and no restraint beams) and the shape of the cross-section has been optimized, by increasing or decreasing the material thickness in places, in order to limit radial deformation. This design has been developed to allow the manufacturing by an extrusion moulding process, which reduces the manufacturing costs in comparison with the moulding process of the fibre-reinforced FMA.

B) Example of a chambers actuator presenting two balloons in a bellows tube: the "Fluidic Bellows Manipulator"

A "Fluidic Bellows Manipulator" is presented in [25]. It comprises two vulcanized balloons placed in an elastomer bellows tube, closed at both ends (see Fig. 2.8). The bellows tube is made of an alternation of rigid and compliant rings which enable the tube to bend and stretch. A polycarbonate floating spine, stiffened by a high-strength steel sheet, separates the balloons.

To operate the device, it has to be fixed at one end while the other remains free. When a balloon is inflated with air, it expands and the floating spine shifts and takes the shape of the tube wall (see Fig. 2.9). The inflated balloon applies a force to the inner side of the device tip and generates a bending moment with respect to the neutral axis of the structure and this involves the bending of the manipulator. An equilibrium position is reached when this bending moment is balanced by the bending moments corresponding to the deformations of the floating spine and of the tube. Fig. 2.10 presents the actuator bending when one balloon is pressurized with a given pressure and when the actuator is loaded by a weight hung at its end.

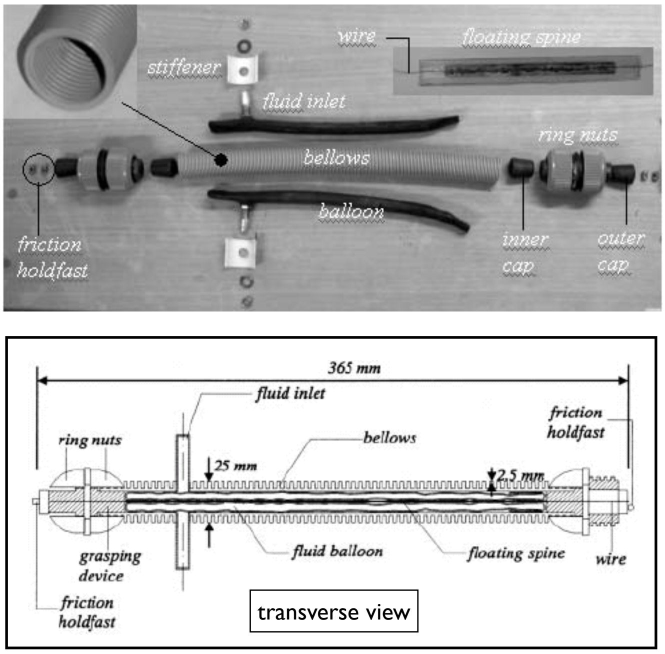


Figure 2.8: Parts of the Fluidic Bellows Manipulator: it comprises two vulcanized balloons placed in an elastomer bellows tube, closed at both ends. The bellows tube is made of an alternation of rigid and compliant rings which enable the tube to bend and stretch. A polycarbonate floating spine, stiffened by a high-strength steel sheet, separates the balloons. Upper figure from [25] and lower figure adapted from [25].

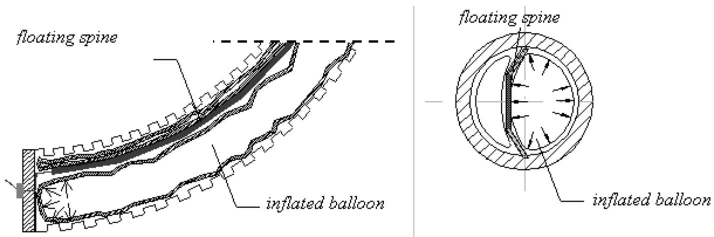


Figure 2.9: Views of the inside of the Fluidic Bellows Manipulator when it is actuated: when a balloon is inflated with air, it expands and the floating spine shifts and takes the shape of the tube wall. The inflated balloon applies a force to the inner side of the device tip and generates a bending moment with respect to the neutral axis of the structure and this involves the bending of the manipulator. An equilibrium position is reached when this bending moment is balanced by the bending moments corresponding to the deformations of the floating spine and of the tube. The left figure presents a transverse view of the actuator while the right figure presents a cross-section view. Figures from [25].

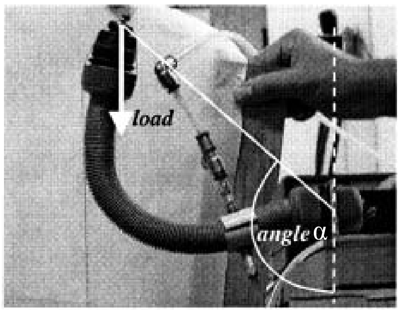


Figure 2.10: Bending Fluidic Bellows Manipulator: one balloon is pressurized with a given pressure and a given weight is hung at the end of the actuator. The bending angle α of the actuator is defined as presented in the figure. Figure adapted from [25].

2.4.3 Bending thanks to anisotropic rigidity

The devices based on this principle present an elongated shape closed at one end and an elongated area whose rigidity is higher than that of the rest of the device. This difference in rigidity is called "anisotropic rigidity". Fig. 2.11 presents such an actuator whose right side is more rigid than its left side. When the device is pressurized, the length of the stiffer area increases less than the rest of the device and consequently the device bends.

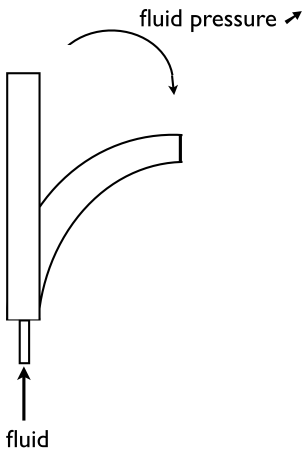


Figure 2.11: Side view of a device bending thanks to anisotropic rigidity. The right side is more rigid than the left side. When the device is pressurized, the length of the stiffer side increases less than that of the other side and consequently the device bends.

Anisotropic rigidity can be achieved by different ways (see Fig. 2.13 and 2.14):

- by using different thicknesses of material in the actuator, the thicker area being stiffer than the rest of the device (see no. 1 in Fig. 2.13).
  [42] presents an example of such an actuator.
- by using different materials presenting different rigidities (see no. 2 in Fig. 2.13).

The "Pneumatic Balloon Actuator" of [49] is such an actuator and it will be described in more details later.

- by fixing inextensible fibres or sheets to the actuator or by embedding them in its material (see no. 3 in Fig. 2.14).
  The "FMA gripper" of [73] is such an actuator and it will be described in more details later. Other examples can be found in [37] (inextensible fibre fixed to the actuator), [35] (inextensible sheet fixed to the actuator) or [84] (inextensible fibre embedded in the rubber of the actuator).

- by weakening an area of the actuator with incisions, bellows, etc (see no. 4 in Fig. 2.14).
  For example, the "Hydraulic Suction Active Catheter" presented in [59] (see Fig. 2.12) belongs to this category. It is composed of a Ti-Ni super elastic alloy structure (processed by laser ablation) and of a flexible tube (of silicone rubber) covering the Ti-Ni structure. The Ti-Ni structure consists of rings connected by "meandering beams" (see Fig. 2.12) and it creates the anisotropic rigidity of the device. The catheter is filled with water and the suction of it involves the bending of the device.

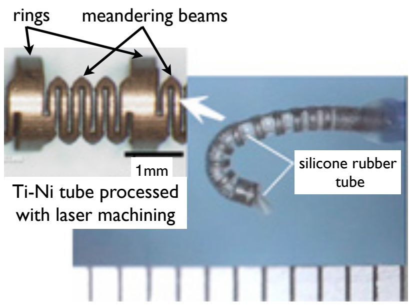


Figure 2.12: Hydraulic Suction Active Catheter: it is composed of a Ti-Ni super elastic alloy structure and of a flexible tube (of silicone rubber) covering the Ti-Ni structure. The Ti-Ni structure consists of rings connected by "meandering beams" and it creates the anisotropic rigidity of the device. The catheter is filled with water and the suction of it involves the bending of the device. Figure adapted from [59].

Concerning the "Hydraulic Forceps" of [53], it is an actuator bending thanks to the presence of incisions in its structure; it will be described in more details later. Other examples can be found in [47] and [45] (actuators bending thanks to the presence of bellows in their structure).

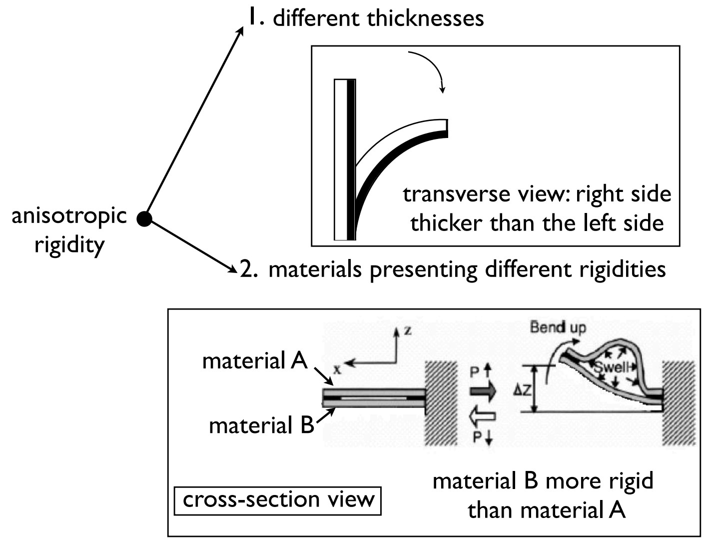


Figure 2.13: Flexible fluidic actuators bending thanks to "anisotropic rigidity". These actuators present an elongated shape closed at one end and an elongated area whose rigidity is higher than that of the rest of the device. This difference in rigidity is called "anisotropic rigidity". When the device is pressurized, the length of the stiffer area increases less than the rest of the device and consequently the device bends. Anisotropic rigidity can be achieved by different ways such as using different material thicknesses in the actuator or using different materials presenting different rigidities (figure adapted from [49]).

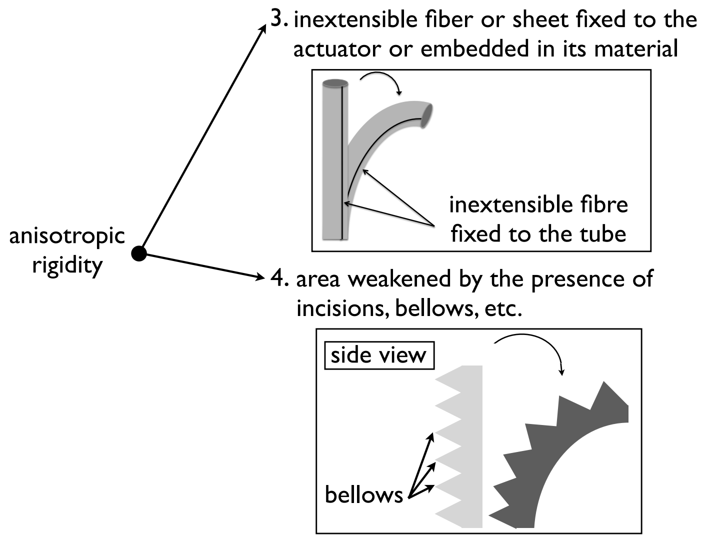


Figure 2.14: Flexible fluidic actuators bending thanks to "anisotropic rigidity". These actuators present an elongated shape closed at one end and an elongated area whose rigidity is higher than that of the rest of the device. This difference in rigidity is called "anisotropic rigidity". When the device is pressurized, the length of the stiffer area increases less than the rest of the device and consequently the device bends. Anisotropic rigidity can be achieved by different ways such as fixing inextensible fibres or sheets to the actuator or embedding them in its material or weakening an area of the actuator with incisions, bellows, etc.

A) An example of anisotropic rigidity achieved by using different materials presenting different rigidities: the "Pneumatic Balloon Actuator" (PBA)

In [49], Konishi et al. propose a "Pneumatic Balloon Actuator" (PBA). This device is fixed as a cantilever and comprises two flexible films. The upper one acts as a membrane and is a silicone rubber film while the lower one plays the role of a substrate and is a polyimide film (see the left part of Fig. 2.15). This difference in the film rigidities involves anisotropic rigidity. The films are glued to one another along their surrounding edge with silicone rubber glue and this configuration forms a cavity. When pressurized air is introduced in this cavity, the silicone rubber film inflates without supporting any bending load (like a membrane). On the other hand, the polyimide film bends due to the moment produced by the tensile forces in the membrane. This behaviour results in a large out-of-plane vertical displacement (i.e. in the y-direction in Fig. 2.15) and in a horizontal displacement (i.e. in the x-direction in Fig. 2.15) of the free end of the actuator.

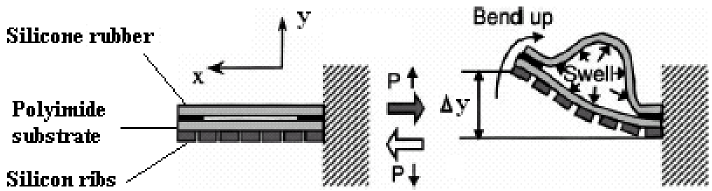


Figure 2.15: Working principle of a Pneumatic Balloon Actuator (PBA), cross-section views: PBA at rest and pressurized PBA (P = pressure) on the left hand side and the right hand side respectively. The PBA is fixed as a cantilever and comprises two flexible films. The upper one acts as a membrane and is a silicone rubber film while the lower one plays the role of a substrate and is a polyimide film. When pressurized air is introduced in the PBA, the silicone rubber film inflates without supporting any bending load and the polyimide film bends due to the moment produced by the tensile forces in the membrane. Figure adapted from [49].

In Fig. 2.15, one can notice the presence of ribs below the polyimide film. These are silicon ribs (obtained by dicing a silicon beam) glued to the substrate and aimed at preventing an unwanted swelling of the substrate and at forcing the device to bend around the z-axis of the ribs, in order to avoid an unwanted corner folding [49].
In order to miniaturize the PBA, the air compressor, that had been used, needed to be replaced and the authors considered and successfully tested a "liquid to gas" phase transformation by Joule heating, to obtain the pressure supply.
Miniaturized PBAs can be achieved thanks to micromachining. Indeed, the planar structure of the PBA suits this technique well and allows distributed micro PBA arrays to be produced in batches.
PBAs have been used to make a "ciliary motion conveyance system" in which they have to work in a co-operative way to displace an object horizontally, such as a glass plate for example. Another application is a two DOFs actuator comprising two PBAs.
In [50], Konishi et al. describe micro PBAs which have been used to actuate a micro hand. They are composed of two layers of different thicknesses made of PDMS elastomer, one of the layers presenting a cavity. When the same PDMS is used for both layers, the PBA presents a bidirectional bending motion. Indeed, when fixed as a cantilever (with the thicker layer below) and pressurized, the PBA moves its end upwards, until a given pressure level is reached; above this level, the PBA tip is moved downwards. On the other hand, a unidirectional bending motion (i.e. upwards motion only) is achieved in the case of a PBA whose layers are

made of different PDMS.

The micronsize "Balloon-Jointed Micro-fingers" presented in [55] (see Fig. 2.16) work on the same principle as the PBA. These fingers are made of two silicon parts jointed by a Parylene balloon. The balloon comprises two membranes: the upper one is free to deform while the lower one is fixed and unable to inflate. When the balloon is pneumatically pressurized, the upper membrane inflates and pulls on the silicon parts, involving the finger to close itself.

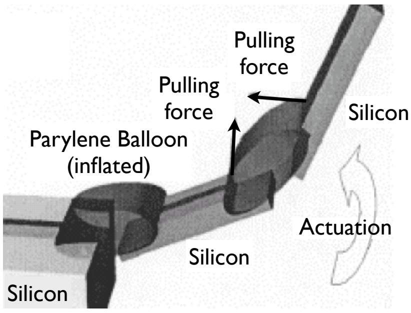


Figure 2.16: Balloon-Jointed Micro-finger: it is made of two silicon parts jointed by a Parylene balloon. The balloon comprises two membranes: the upper one is free to deform while the lower one is fixed and unable to inflate. When the balloon is pneumatically pressurized, the upper membrane inflates and pulls on the silicon parts, involving the finger to close itself. Figure from [55].

B) An example of anisotropic rigidity achieved by fixing inextensible fibres or sheets to the actuator or by embedding them in its material: the FMA Gripper

A gripper placed at the end of an FMA is presented in [73]. Fig. 2.17 shows this gripper, made of rubber-like material. It comprises an internal chamber whose four sides A, B, C and D are fibre-reinforced in the transverse direction. Besides, fibres reinforce side C in the longitudinal direction and cause anisotropic rigidity. Consequently, when the pressure is increased in the chamber, the gripper bends to side C (dashed-dotted lines in Fig. 2.17) and if an object is placed between the plate and side C, it will be gripped.

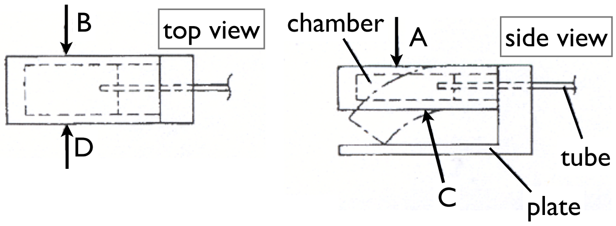


Figure 2.17: Views of the FMA Gripper: gripper at rest and pressurized gripper in continuous and dash-dotted lines, respectively. Fibres reinforce side C in the longitudinal direction. Consequently, when the pressure is increased in the chamber, the gripper bends to side C and if an object is placed between the plate and side C, it will be gripped. Figure adapted from [73].

C) An example of anisotropic rigidity achieved by weakening an area of the actuator with incisions, bellows, etc.: the "Hydraulic Forceps"

[53] presents a "Hydraulic Forceps". A forceps is a medical tool used during MIS operations "*to move tissue away from the operation field or to stretch tissue that has to be dissected*" [53].
The Hydraulic Forceps presents two tubes (see Fig. 2.18): a very flexible material is used for the inner tube, which contains water, while a stiffer material has been chosen for the outer tube. As can be seen in Fig. 2.18, small incisions have been performed in the outer tube, perpendicularly to it and these involve anisotropic rigidity. Both tips of both tubes are fixed to each other and this implies equal deformations of the tubes.

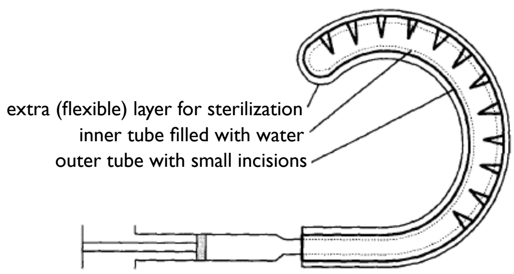


Figure 2.18: Working principle of the Hydraulic Forceps: when filled with pressurized water, the forceps curls due to the incisions in the outer tube. Figure from [53].

When the pressure of water is increased, axial and radial forces are generated. The radial forces do not participate to the bending of the device because they are applied over the total length of the tubes. On the other hand, the axial forces are applied to the end of the tubes and are at the origin of the bending. The outer tube carries most of the axial forces because its stiffness is bigger than that of the inner tube. More precisely, the axial forces are distributed only over one half of the cross-section of the outer tube because of the presence of the small incisions in the other half. This asymmetrical force distribution creates a bending moment which involves the bending of the entire device.
The forceps has been integrated in a teleoperation system with force feedback. A manipulator actuated by the surgeon's finger constitutes the master device of this system while the hydraulic forceps is its slave device. When the surgeon moves the master, the slave has to reproduce its movements, i.e. the evolution of the surgeon's finger curvature. On the other hand, force feedback aims at making the surgeon feel the forces applied to the forceps and it is obtained by measuring and introducing these forces to the master.
The principle of the forceps is said to be suitable for other (surgical) applications where the handling of soft objects is required and it could also be used for the positioning of instruments in fields such as endoscopy or robotics [53].

2.4.4 Rotation

This section presents actuators having a rotational ability. As shown in Fig. 2.19, two ways of generating a rotational motion have been found in the literature:

- Some actuators are based on a structure reinforced in places (with fibres or by increasing the material thickness) in such a way that when the actuator is pressurized, its structure involves a rotation (see no. 1 in Fig. 2.19). The "Pneumatic Rotary Soft Actuator" of [60] is such an actuator and it will be described later in more details.

- Another way to generate a rotational motion consists in an articulated structure in which one or several flexible fluidic actuators are inserted (see no. 2 in Fig. 2.19). These actuators present only one DOF, such as stretching, shortening or expanding. When the actuators are pressurized, they actuate the structure which involves a rotation. For example, an antagonistic structure in which two Pneumatic Artificial Muscles are inserted is a system belonging to this second category. This example and three others will be described later in more details.

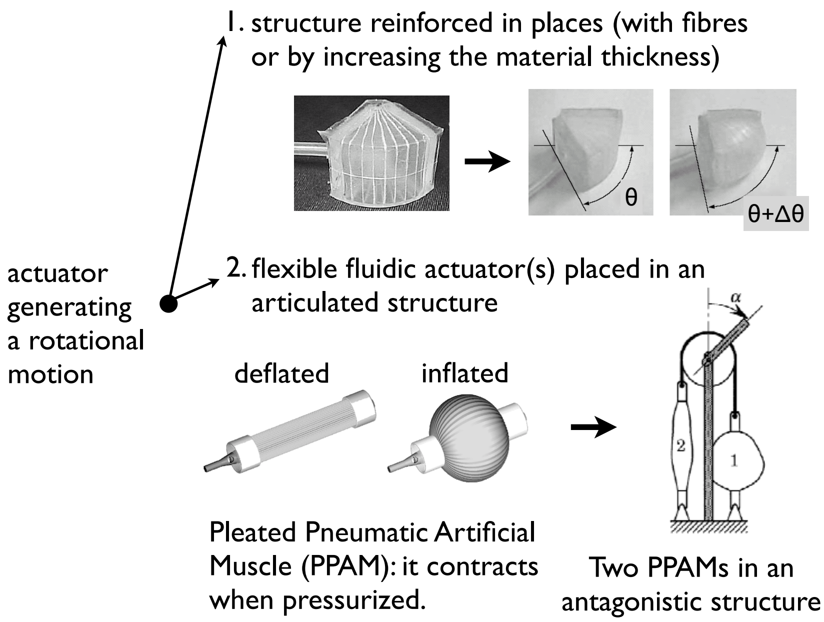
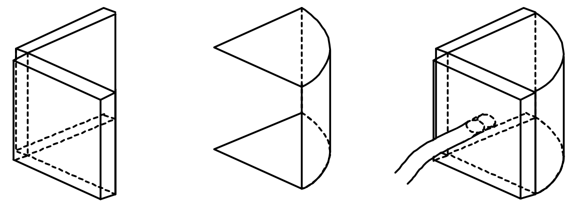


Figure 2.19: Two ways of generating a rotational motion: Some actuators are based on a structure reinforced in places (with fibres or by increasing the material thickness) in such a way that when the actuator is pressurized, its structure involves a rotation (figures from [60]). Another way to generate a rotational motion consists in an articulated structure in which one or several flexible fluidic actuators are inserted. These actuators present only one DOF, such as stretching, shortening or expanding. When the actuators are pressurized, they actuate the structure which involves a rotation. For example, an antagonistic structure in which two Pneumatic Artificial Muscles are inserted is a system belonging to this second category (figures from [83] and [31]).

A) An example of rotational motion achieved thanks to a structure reinforced in places: the "Pneumatic Rotary Soft Actuator"

In [60], a pneumatic actuator made of silicone rubber is described (see Fig. 2.20). It is called "Pneumatic Rotary Soft Actuator". This actuator acts as a rotary joint and can be used in micro-manipulators and fingers. It is composed of two side plates (see (a) in Fig. 2.21), a sector circular arc (see (b) in Fig. 2.21) and a pneumatic tube (see (c) in Fig. 2.21) which is connected to one of the side plates and which feeds the actuator with air.

Figure 2.20: Pneumatic Rotary Soft Actuator. This actuator is made of silicone rubber and fibres and it acts as a rotary joint. Figure from [60].



(a) (b) (c)

Figure 2.21: Parts of the Pneumatic Rotary Soft Actuator: (a) two side plates (b) sector circular arc (c) two side plates + sector circular arc + tube = complete Pneumatic Rotary Soft Actuator. Figure from [60].

The thickness of the side plates is higher than that of the sector circular arc, which is reinforced thanks to fibres placed in the radial and vertical directions (see Fig. 2.20). When the device is pressurized, the thickness of the side plates prevents them from deforming while the radial deformation of the sector circular arc is hindered by the fibres. Consequently the device expands only in the circumferential direction, its opening angle is increased and a rotation is achieved (see Fig. 2.22).

To manufacture the different components of the actuator, liquid silicone rubber is poured into metal moulds and left to harden. Two additives, a hardener and a diluent (called "RTV thinner"), are mixed in the rubber. Changing the quantity of the diluent allows to control the stiffness obtained after hardening.
Two pressurized tubes and a rotary soft actuator have been used as phalanxes and joint, respectively, to construct a soft finger. Changing the inner pressure of the tubes allows to modify the compliance of the finger. A soft hand comprising three soft fingers has also been developed and has allowed to grip objects moving in arbitrary directions, objects presenting different shapes and easily deformable objects.

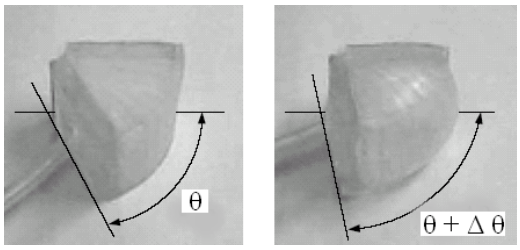


Figure 2.22: Actuation of the Pneumatic Rotary Soft Actuator: when the device is pressurized, the thickness of the side plates prevents them from deforming while the radial deformation of the sector circular arc is hindered by the fibres. Consequently the device expands only in the circumferential direction, its opening angle θ is increased and a rotation is achieved. Figure from [60].

B) First example of rotational motion achieved thanks to an articulated structure in which one or several flexible fluidic actuators are inserted: an antagonistic architecture in which "Pneumatic Artificial Muscles" (PAMs) are inserted

"Pneumatic Artificial Muscles" (PAMs) are made of a flexible closed membrane that is reinforced and fixed to fittings at both ends. When pressurized gas is introduced in such a device (when gas is sucked out), the membrane bulges out (squeezes) and contracts axially (see Fig. 2.23) [31]. A PAM is then able to pull a load attached to one of its ends.

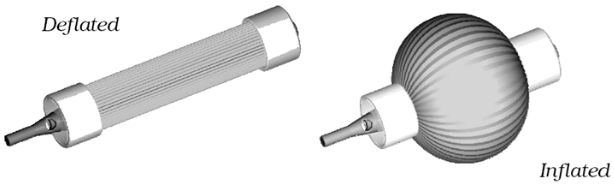


Figure 2.23: Deflated and inflated states of a Pneumatic Artificial Muscle (PAM) presenting a pleated structure. When pressurized gas is introduced in this PAM, the membrane bulges out and contracts axially. Figure from [83].

Although they can only contract, perform linear motion and develop pulling force, PAMs can generate a rotation when used in an antagonistic set-up, as shown in Fig. 2.24. Antagonistic architectures are composed of two muscles but they can be used with other types of contracting actuators. Some architectures allow to obtain a bidirectional rotation but others allow a bidirectional linear motion [31].

A detailed description of the different kinds of PAMs can be found in [29], [31], [48], etc. According to [31], the PAM's behaviour rules are the following:

- "*A PAM shortens by increasing its enclosed volume.*"
- "*It will contract against a constant load if the pneumatic pressure is increased.*"
- "*A PAM will shorten at a constant pressure if its load is decreased.*"
- "*Its contraction has an upper limit at which it develops no force and its enclosed volume is maximal.*"

- "*For each pair of pressure and load a PAM has an equilibrium length*".

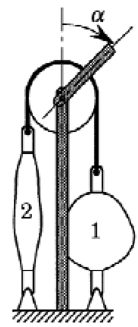


Figure 2.24: Antagonistic set-up generating a bidirectional rotational motion. It is composed of two Pneumatic Artificial Muscles (PAMs) and of an articulated structure. When one of the PAMs is pressurized, it contracts and actuates the structure which generates a rotational motion. Figure from [31].

The PAM's behaviour contrasts with that of bellows which stretch when pressurized. It also differs from the behaviour of a pneumatic cylinder which develops the same force for a constant pressure, whatever the piston displacement (while, at constant pressure, a PAM develops a different pulling force according to its length).
PAMs are mostly used in robotic applications where two important features are the compliance and a high power to weight ratio [31]. For example, they actuate the anthropomorphic robot LUCY [83] and [31] relates applications such as prosthesis/orthotics and an underwater manipulator (for which the driving fluid was water without causing weight problems because the surrounding fluid was also water). At present, the company Festo Ag. & Co. [38] sells fluidic muscles which can be used in a wide range of applications such as positioning systems, machining, etc.
Remark: According to [31], the McKibben PAM "*is the most frequently used and published about at present*".

C) Second and third examples of rotational motions achieved thanks to an articulated structure in which one or several flexible fluidic actuators are inserted: the "Expansion Behaviour Based Actuators" (EBBAs) and the "Pneumatically Driven Microcage"

In [69], small size flexible fluidic actuators, based on an "expansion behaviour", are presented. They will hereafter be referred to as "EBBAs" (="Expansion Behaviour Based Actuators"). These actuators consist of a chamber connected to two movable parts. When pressurized fluid (air or liquid) is introduced in the chamber through a feeding channel, the volume and height of the chamber increase, involving the movable parts to move relatively to each other. This is what is called the "expansion behaviour". Different kinds of joints can be obtained by using EBBAs. For example, to design a linear joint, two parallel plates can be linked by a chamber in such a way that a pressure rise increases the gap between the plates while keeping them parallel. On the other hand, a rotation joint can be achieved with a chamber placed between two movable parts linked by a joint; a pressure increase then involves a rotation of the movable parts, as shown in Fig. 2.25.

Figure 2.25: Rotation joint composed of a chamber placed between two movable parts linked by a joint. When the pressure in the chamber is increased, a rotation of the movable parts is involved. Figure from [69].

EBBAs are said to present high flexibility (due to their mechanical construction), are lightweight and have a very low manufacturing cost. Besides, using several EBBAs enables to achieve very complex motions.
An artificial hand, based on these actuators, has been developed. It is equipped with miniaturized rotation joints based on EBBAs and integrated into the fingers and the wrist. Many different objects can be grasped by the hand which adapts itself to their shape, thanks to the EBBAs' flexibility. Moreover, it performs movements that appear very natural.

In [62], a "Pneumatically Driven Microcage" is presented. This device aims at capturing microscale objects in biological liquid. It works on the same principle as the EBBAs; the deformation of an elastic membrane is used to achieve the displacement of rigid parts. The cage consists of curved beams or fingers placed in a circular manner and resting on a rubber membrane. When the pressure under the membrane is increased, the latter inflates and involves the rotation of the beams and thus the opening of the cage (see Fig. 2.26).

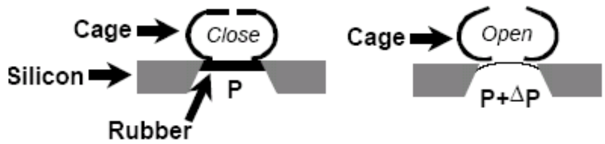


Figure 2.26: Actuation of the Pneumatically Driven Microcage: the cage consists of curved beams or fingers placed in a circular manner and resting on a rubber membrane. When the pressure under the membrane is increased, the latter inflates and involves the rotation of the beams and thus the opening of the cage. Figure adapted from [62].

D) Fourth example of rotational motion achieved thanks to an articulated structure in which one or several flexible fluidic actuators are inserted: the Torsion joint based on Flexible Pneumatic Actuators (FPAs)

A "Flexible Pneumatic Actuator" (FPA) is presented in [84]. It is a hollow cylinder made of elastic rubber (see no. 3 in Fig. 2.27) and containing a spiral steel wire (see no. 2 in Fig. 2.27). This wire reinforces the cylinder and prevents its deformation in the radial direction. Covers (see no. 4 in Fig. 2.27) close both ends of the device and an air feeding tube (see no. 1 in Fig. 2.27) is connected to one of them. When the FPA is pressurized, the cylinder expands in the axial direction without any other deformation. When the pressure is decreased, it goes back to its initial state thanks to the elasticity of the rubber.

A torsion joint based on FPAs has been developed (see Fig. 2.28); it is composed of a steady plate (see no. 3 in Fig. 2.28), a moving plate (see no. 1 in Fig. 2.28) and two FPAs (see no. 2 in Fig. 2.28). The moving plate is connected to the steady plate through a bearing and the FPAs' ends are fixed to each plate. When the air pressure is increased in the FPAs, they expand, push on the moving plate and force it to turn around its axis.

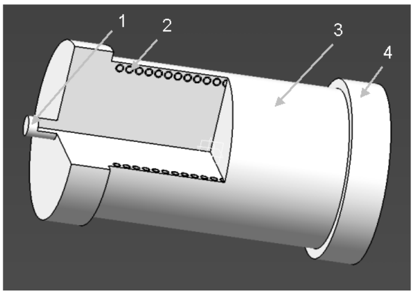


Figure 2.27: Structure of a Flexible Pneumatic Actuator (FPA): 1) Air feeding tube 2) Spiral steel wire 3) Elastic rubber cylinder 4) Cover. An FPA is a hollow cylinder made of elastic rubber and containing a spiral steel wire. This wire reinforces the cylinder and prevents its deformation in the radial direction. When the FPA is pressurized, the cylinder expands in the axial direction without any other deformation. Figure redrawn and adapted from [84].

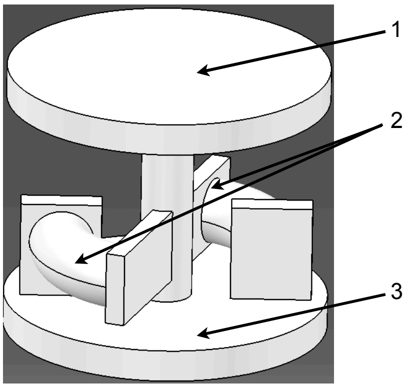


Figure 2.28: Torsion joint based on Flexible Pneumatic Actuators (FPAs): 1) Moving plate 2) Two FPAs 3) Steady plate. The moving plate is connected to the steady plate through a bearing and the FPAs' ends are fixed to each plate. When the air pressure is increased in the FPAs, they expand, push on the moving plate and force it to turn around its axis. Figure redrawn and adapted from [84].

2.4.5 Stretching or shortening

Some flexible fluidic actuators are able to stretch themselves or to shorten when they are pressurized. They are listed below:

- Stretching ability:
  - bellows (see no. 1 in Fig. 2.3)
  - the "Flexible Pneumatic Actuator" (FPA) presented in Fig. 2.27
- Shortening ability:
  - the "Pneumatic Artificial Muscles" (PAMs) (see Fig. 2.23)

– an elastic tube with fibres fixed to it in the axial direction (see no. 3 in Fig. 2.3)

Besides, all the actuators that bend thanks to internal chambers differently pressurized (see Section 2.4.2) can stretch themselves or shorten when all their chambers are equally pressurized.

2.5 Conclusions

Flexible fluidic actuators present interesting characteristics regarding an application in the field of robotics or inside the human body. According to the application targeted, it might be necessary to miniaturize the actuators but also their peripherics and some solutions have been presented in this respect.

At the light of the literature review, it has been established that the flexible fluidic actuators can bend themselves, stretch themselves, shorten or develop a rotational motion and some of them present several DOFs. Two different methods to achieve bending have been identified. The first technique is based on "internal chambers differently pressurized" and the other one on "anisotropic rigidity". Besides, two methods to generate a rotational motion have also been identified. The actuators based on the first technique present a structure reinforced in places (with fibres or by increasing the material thickness) in such a way that when the actuators are pressurized, their structure involves a rotation. The second method to generate a rotational motion consists in an articulated structure in which one or several flexible fluidic actuators are inserted. When the actuators are pressurized, they actuate the structure which involves a rotation.
There exists a multitude of flexible fluidic devices and additional actuators can be obtained by combining different principles, in order to achieve more or less DOFs. Hence, this review can helps to develop medical flexible instruments based on flexible fluidic actuators. Besides, tools to be placed at the tips of the instruments could also be designed and based on flexible fluidic actuators such as, for example, the Hydraulic Forceps, the FMA Gripper or the Pneumatically Driven Microcage.

According to the bulkiness that is allowed for the instrument in the targeted application, it will be necessary to assess the miniaturization potential of the actuators presented in the review. In this respect, actuators presenting a simple structure with a small number of parts will be better candidates to design miniature instruments. Hence, the actuators that seem to have the best miniaturization potential in each category are the following:

- Bending thanks to internal chambers differently pressurized: the "Flexible Microactuator" (FMA) (see Fig. 2.6)
- Bending thanks to anisotropic rigidity: the four ways presented in Fig. 2.13 and 2.14 can lead to actuators quite easy to miniaturize. In the actuators presented in details, the "Pneumatic Balloon Actuator" (PBA, see Fig. 2.15) and the FMA gripper (see Fig. 2.17) are good candidates.
- Rotational motion: the actuators based on a structure reinforced in places and designed to develop a rotational motion are better candidates to be miniaturized than those based on an articulated structure.
- Stretching ability: bellows (see no. 1 in Fig. 2.3) and the "Flexible Pneumatic Actuator" (FPA) presented in Fig. 2.27
- Shortening ability: an elastic tube with fibres fixed to it in the axial direction (see no. 3 in Fig. 2.3)

Finally, it is worth noting that preventing unwanted deformations of the membranes, thanks to fibres or a larger thickness at strategic places, is a rule of design that permeates this review.

Tables 2.1 and 2.2 summary the characteristics of most of the actuators described in this review. These characteristics are the DOFs, the materials, the manufacturing process, the actuator dimensions, the actuation mode (pneumatic or hydraulic), the pressure range and the performances in terms of developed force and displacement.
Remark: Complementary information about some of the actuators mentioned in the review can be found in [40] as well as a series of patented flexible fluidic actuators sorted into the different categories.

Among the interesting features linked to the use of flexible fluidic actuators, one has caught our eye. Indeed, in [78], the "Flexible Microactuator" (FMA) is presented and it is suggested that the measurements of the fluid pressure and of the volume of supplied fluid allow to determine and control the position of the actuator and the force it develops. This property has been called the "Pressure-Volume-Force-Position principle" or "PVFP principle" and it means being able to determine the displacement of a flexible fluidic actuator and the force it develops without using a displacement sensor or a force sensor [78].
To study and implement this principle, that could have applications in the medical field, a flexible fluidic actuator having a simple design, one DOF and which is easily manufactured has been looked for in the review presented above and the "Pneumatic Balloon Actuator" (PBA) has been selected. The implementation of the PVFP principle on this actuator is detailed in Chapter 5.

A miniaturization work has been performed on a special type of Pneumatic Artificial Muscle called the "Pleated Pneumatic Artificial Muscle" (PPAM). Although it is not one of the better candidates to be miniaturized, this actuator has been selected because it can generate large forces and theoretical models predict that miniaturized PPAMs, whose dimensions are small enough to be inserted into MIS medical instruments, could be able to develop the forces required to allow the instruments to perform most surgical actions (see Section 3.2.2 and Table 3.1). Therefore, the PPAMs have been studied in order to assess their miniaturization potential; this is detailed in Chapter 7.

Device	Actuation mode	Pressure range	Dimensions	DOFs	Materials
FMA reinforced with fibres [72]-[71]	P or H	some bar	D: 1 to 20 mm	3 $S, 2B_1$	silicone rubber and nylon fibres
FMA with restraint beams [75]	P or H	some bar	reported values of D: 1.8 mm and 4.8 mm	3 $S, 2B_1$	rubber-like material reacting to UV light
Optimized fibreless FMA [77]	P or H	some bar	initial D: 1 to 100 mm initial L: 2 to 100 times D	3 $S, 2B_1$	rubber-like material
Positioning system for catheter tips [67]	P	0.1 to 0.2 bar	1 balloon : maximum $D = 3$ mm $L = 4$ mm	2 $2B_1$	balloon: polyurethane
Fluidic Bellows Manipulator [25]	P	up to 4 bar	$D = 25$ mm / $L = 365$ mm	2 S, B_1	vulcanized balloons, elastomer tube, ABS parts, steel wire, spine (polycarbonate + high-strength steel sheet)
Suction Active Catheter [59]	H	up to 0.8 bar	$L = 5.5$ mm $D = 0.94$ mm	1 B_2	Ni-Ti tube, silicone rubber tube
Balloon Jointed Micro-Finger [55]	P	0 to ≈ 8 bar	1 finger = 2 blocks (900 µm X 300 µm, $t = 200$ µm) + 2 balloons (540 µm X 640 µm, $t = 6$ µm)	1 B_2	blocks: silicon balloons: parylene
PBA [49]	P	up to 0.6 bar	$L = 16$ mm $l = 16$ mm $t = 775$ µm	1 B_2	polyimide film, silicone rubber membrane, (silicone rubber glue)
Micro PBA [51] [50]	P	0 to 2.1 bar	1 PBA : $W = 300$ to 700 µm $L = 700$ to 1500 µm	1 B_2	2 PDMS with different stiffnesses
FMA Gripper [73]	P or H	some bar	$L = 18$ mm / $l = 8$ mm	1 B_2	rubber-like material and nylon fibres
Hydraulic Forceps [53]	H	not specified	not specified	1 B_2	flexible material
Pneumatic Rotary Soft Actuator [60]	P	up to 0.4 bar	side plate: 17 mm × 17 mm, $t = 3$ mm sector circular arc: $t = 0.5$ mm max opening angle: 85°	1 R	silicone rubber, fibres
FPA [84]	P	up to 3.5 bar	not specified	1 S	elastic rubber, steel wire
EBBA rotation joint [69]	P or H	up to 0.5 bar	not specified	1 R	flexible material
PAM [31]	P or H	up to max 5 - 8 bar	see [31]	1 Sh	see [31]

Table 2.1: Characteristics of the flexible fluidic actuators presented in Section 2.4. "P", "H", "D", "L", "l" and "t" mean "pneumatic", "hydraulic", "diameter", "length", "width" and "thickness", respectively. "S", "Sh", "B_1", "$2B_1$", "B_2" and "R" mean "stretching ability", "shortening ability", "bending thanks to chambers differently pressurized", "two bending motions thanks to chambers differently pressurized", "bending thanks to anisotropic rigidity" and "rotation ability", respectively. Concerning the positioning system for catheter tips, two bending DOFs are mentioned in [67] but a third DOF (a stretching DOF) is probably available.

Device	Manufacturing Process	Results
FMA reinforced with fibres [72]-[71]	Moulding	$D = 12$ mm / $L = 50$ mm $p = 4$ bar in one chamber / $\lambda = 100°$
FMA with restraint beams [75]	Stereolithography	$restr = 2$ / $D = 4.8$ mm / $L = 15$ mm $p = 3$ bar in one chamber / $\lambda \approx 60°$
Optimized fibreless FMA [77]	Extrusion moulding process	$p = 4$ bar $\lambda = 90°$
Positioning system for catheter tips [67]	balloons: polyurethane tubes locally widened other parts : moulding	into a glass tube with 4 mm inner diameter $p = 0.15$ bar / maximum deflection $= 5°$ maximum lateral displacement $= 0.5$ mm
Fluidic Bellows Manipulator [25]	Not specified	$W \approx 0.13$ kg / $p = 4$ bar in one balloon $F_v = 9$ N (2 N) / $\alpha = 30°$ (115°)
Suction Active Catheter [59]	Ni-Ti tube: laser ablation	curvature radius $= 1.4$ mm $\lambda = 160°$
Balloon Jointed Micro-Finger [55]	RIE etching + vapor phase deposition of parylene	$p \approx 4$ bar / $F_v = 1.225$ mN (0 N) $\Delta z \approx 300$ µm (760 µm)
PBA [49]	Gluing	$p = 0.2$ bar $F_v = 0.05$ N (0 N) / $\Delta z = 0$ mm (4.5 mm)
Micro PBA [51] [50]	coating, spin-coating and curing processes	-
FMA Gripper [73]	Moulding	able to generate a 2 N gripping force
Hydr. Forceps [53]	Not specified	the prototype succeeded in producing a force of 1 N
Pneumatic Rotary Soft Actuator [60]	Moulding	$p = 0.4$ bar / variation of the opening angle $= 25°$ (0° and opening angle constrained at 65°) / $torque = 0$ Nm (0.15 Nm)
FPA [84]	Not specified	$p = 3.5$ bar / $\Delta L = 10$ mm
EBBA rotation joint [69]	Low cost but not specified	finger equipped with EBBA rotation joints: $W = 20$ g / max force at the finger tip > 3 N for $p = 0.5$ bar / $\Delta t = 100$ ms
PAM [31]	Not specified	Pleated PAM: $p = 3$ bar / $D = 25$ mm / $L = 100$ mm $W = 60$ g / pulling force of 3500 N

Table 2.2: Characteristics of the flexible fluidic actuators presented in Section 2.4. For a given device, all the data presented in column "Results" are part of the same result (data given in brackets constitute a second result). The notations are the following: D=diameter, L=length, W=weight of the device, p=pressure, λ=bending angle (defined as shown in Fig. 2.6), ΔL=lengthening, $restr$=number of FMA restraint beams per chamber, F_v=developed vertical force (the device being initially placed horizontally), α=bending angle of the Fluidic Bellows Manipulator (defined as shown in Fig. 2.10), Δz=vertical out-of-plane displacement of the actuator tip (the device being initially placed horizontally), Δt=duration taken by a finger equipped with EBBA rotation joints to flex completely and to extend.