PART I

Development of Silicone-based Stiffness Controllable Actuators

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Technology Selection

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Abstract

The first step for the development of the soft manipulator starts with the definition of both medical and technical requirements. Within these boundaries, the most suitable technological choices have to be taken. Thus, after the manipulator specifications, a survey of candidate actuation technologies is reported. A direct comparison is also provided to highlight the advantages and disadvantages for the specific application field.

1.1 Manipulator Specifications

The flexible manipulator has been designed to meet specific requirements extracted from medical literature and experience and through *in vivo* biomechanical tests of internal organs. On the basis of the limitations underlined by the current robotic instruments used in surgery and the desired characteristics from a clinician perspective, the technical specifications of the manipulator have been derived.

1.1.1 Medical Requirements

In a clinical setting perspective, the STIFF-FLOP manipulator should have the following characteristics, allowing overcoming the main overall limitations of the current available robotic system:

- *Dimensions and maneuverability:* The STIFF-FLOP manipulator should be limited in its overall dimensions and weight, being these directly related to the maneuverability in the operating room. In this context, it is important to bear in mind how standard operating rooms are limited in spaces and generally contain a great number of medical devices, such as the operating bed, the nurse workstation, the anesthesiologist workstation, trolleys, and wardrobes, together with the operating room staff. Furthermore, a high maneuverability leads to higher surgical safety, since it means that the manipulator can be easily and quickly removed from the surgical bed. Finally, small overall dimensions leave more space for the surgical team, for the nurse, and for the anesthesiologist's access to the patients, and thus, further improve overall surgical safety.
- *Improved operator's autonomy:* An optimal manipulator should be conceived with the main purpose to improve the surgical autonomy of the operator surgeon, allowing him/her to operate without the help of a skilled laparoscopic assistance. In this contest, the expertise level of the assistant surgeon should not represent a critical aspect of the procedure, unlike the current robotic system. Furthermore, a manipulator conceived to be small in dimensions and user-friendly could lead to an improvement in the ergonomics not only of the operating surgeon but also of the assistants.

Other more technical desired features that could increase the usability of the proposed robotic manipulator are as follows:

- *Arms' motion range:* The currently used robotic system arms (i.e., the da Vinci system) have external articulations that limit the motion range of the instruments inside the abdomen: since the internal articulation is limited to the end-effector EndoWrist, the system needs to move the arms outside the abdomen to change surgical target, increasing the fulcrum effect on the abdominal wall port-sites. Consequently, the robotic system is greatly related to the trocars' position, leading to a critical importance of the port-site position. Furthermore, robotic arms, with their external articulation, lead to difficulties in changing the surgical target inside the abdomen, and when it is needed to work in different anatomical districts, it is often necessary to move the entire robotic trolley. This can really limit the range of surgical procedures suitable for robotic surgery. In this context, a robotic arm potentially able to move itself inside the abdomen could greatly overcome these limitations, allowing more complex movements inside the abdomen and proportionally lower movements outside it.

- *Haptic feedback:* An arm which allows the surgeon to have a haptic feedback of the handled tissues is of critical importance in improving surgical performance and in avoiding tissue tears with potentially harmful consequences, such as bowel perforations.
- *Range of instruments:* From a clinical point of view, the robotic arm could not be conceived without envisioning the end-effector of the arm, i.e., the range of available instruments that can be used with the arm defines to a large extent the usability of the entire arm. A wide and complete range of instruments available for the robotic arm would allow avoiding the use of extra ports and the help of one or more assistants. Also, removing the robotic arm from the abdomen and changing the instrument should be easily and quickly done, in order to avoid a lengthening of operative time and a decrease in surgical safety when a rapid change is needed.

1.1.2 Technical Specifications

The characteristics qualitatively described in the previous section have to be translated into technical specifications to lead and steer the design and the fabrication of the device. It should show squeezing capabilities to be able to pass through a traditional trocar port or an umbilical access. An active, flexible, and articulated tip would improve the dexterity of the device thus allowing the performance of surgical tasks, such as suturing, cauterization, etc. The final device should be able to move through a bend of up to 270° around a large organ, grasp that organ, and retain a grip while moving through 20 mm. The manipulator main features consist of bending capability in any direction, active elongation, and selective stiffening.

Based on the above considerations, the specifications for the flexible arm can be summarized as follows:

- Capability to squeeze and pass through a 20 mm port; hence, the manipulator can be employed for umbilical single-port surgery, NOTES surgery [1], and single access surgery;
- Flexible and articulated length of up to 300 mm, enabling it to turn around organs in the thoracic and abdominal cavities, independently on the entrance point;
- Possible elongation of up to 100 mm ($\sim$33%);

- Force of at least 1 N (better if 5 N) to be achieved in stiffened condition at relevant points along the arm, including the tip, in order to meet typical force requirements of manipulation in surgical tasks like displacement of organs during arm motion or organ retraction [2, 3];
- The stiffness of the modules should be controllable, thus allowing to smoothly adapt to soft organs' geometries as well as to become rigid for retraction actions;
- A tool (such as a gripper) should be attached to the module tip and it should be able to exert a force up to 10 N.

Apart from the requirements listed above, haptic feedback and the possibility to combine the manipulator with a series of instruments need to be considered.

1.2 Technological Overview of Different Actuation Strategies

In this section, an overview of different actuation strategies is reported. This represents the very first step of the design phase where, given the manipulator specifications, the most suitable technologies are revised and compared. It is split into two main groups that refer to two different active capabilities: the first is "active motion" and it contains all the technological solutions that can be used to produce a force and a deformation that actively interact with the environment; the second one is "stiffness variation" and reports several solutions to actively vary the stiffness of structures.

1.2.1 Active Motion Technology Survey

The technological solutions considered for the realization of the active motion of the STIFF-FLOP manipulator are reported in this section. A streamlined but complete survey enables a direct comparison that eases the choice of the most suitable technology. This is followed by a detailed analysis of its state of the art.

Actuators represent the real bottleneck in many robotic applications and even if currently the most used technologies are electromagnetic-driven, they present limitations in terms of inertia and back-drivability, stiffness control, and power consumption.

1.2.1.1 Electromagnetic motors

Electromagnetic motors (cable-driven mechanisms or geared) may lead to several advantages in terms of controllability, actuation forces, and speed. Indeed, most of robotic devices use this technology for the actuation. Typically, the motion generated by electromagnetic motors is converted by an appropriate mechanism in order to generate the desired motion such as geared boxes, cables, or hybrid solutions. One of the main disadvantages of the electromagnetic actuators is that they are rigid and thus limit the flexibility of an instrument if embedded on-board. In addition, miniaturized motors do not have the required performances especially in terms of provided torque.

Cable actuation can be an alternative solution, since powerful motors can be embedded outside the robot thus keeping it flexible. The disadvantages of this solution are mainly in the friction losses along the robot due to the cables that may reduce the controllability of the system; in addition in order to provide an effective actuation at a high dexterity (hyper-redundancy), a high number of powerful and thus big actuators are needed externally (as in the case of the da Vinci, where the encumbrance in the surgery room is one of the main limiting factors).

1.2.1.2 Electro active polymers

In the last few years, new and promising technologies [4] are emerging thus offering new possibilities to fill the gap between natural muscles and artificial artifacts. Most of them are based on polymeric matrixes activated with different mechanisms (**Electro Active Polymers**, EAP) [5, 6].

Dielectric elastomers can be used with different structural configurations to perform an electrical squeezing [7]. The most interesting and functional solution consists in stacking many units composed by dielectric material and electrodes in order to exploit the axial contraction of each unit [8, 9]. *Ferroelectric polymers* have the characteristic to lose their natural polarization when over their Curie point. Zhang et al. found that the copolymers under a proper irradiation treatment exhibit very little room temperature polarization hysteresis and larger electrostrictive strain [10]. *Liquid crystal elastomers* (LCEs) are thermally actuated to produce macroscopic and anisotropic shape changes [11]. Stacks of very thin layers can be manufactured to produce fast and relatively high contractions [12]. *Conductive polymers* (or conjugated polymers) can change their dimensions thanks to the ability to lose or acquire ions when a voltage is applied [13] and most used materials are polypyrrole [14] and polyaniline. By using these materials, the authors of [15] produced PAN fibers and investigated the possibility to use them as linear actuators in wet and dry conditions. *Polymer gels* are able to swell through the uptake of a solvent within a polymer matrix and this process can be affected by electrical means. Gel actuators can exhibit relatively rapid response (0.1 s or less) provided that their surface area to volume ratios are high enough to reduce solvent diffusion times. At the University of Reading, researchers developed essentially Mckibben-type actuators in which the gel replaces the gas [16]. *Carbon nanotubes* were shown to generate higher stresses than natural muscle but lower strains than other polymer-based technologies [17]. *Ionic polymer/metal composites* [18] are based on migration of ions due to application of voltage. They are mainly used for the ability to bend themselves [19–22] but also to vary the stiffness of a structure [23].

These technologies show different performances, some advantages, and several constraints [24], but currently there are no satisfying solutions to imitate natural muscles [25].

1.2.1.3 Shape memory alloys

Shape memory alloys (SMA) [26] are increasingly used in biomimetic robots as bioinspired actuators. There are several kinds of alloys that can be used with different performances. The response time depends on the time needed to pass from the martensitic to the austenitic phase, and consequently it depends on the current that passes through the wires, the dimensions, and the thermal coefficient. A trade-off between current and velocity has to be found, but an acceptable frequency of contraction/relaxation can be reached with a well-designed geometry. SMA has a high force to mass ratio, is lightweight, and compactness, and, for these reasons, it represents a very interesting technology in the prosthetic field [27]. Nevertheless, SMA shows several limitations, like: difficulty in controlling the length of the fibers as they undergo the phase transition first of all due to their hysteresis; dependence of the bandwidth on heating and cooling rates; and limited lifecycles. These data depend on the percentage of contraction that has to be reached (300 for 5%, 10,000 for 0.5%) [24]. Despite that, there are several examples (especially in the biomimetic field) that demonstrate the real possibility to use this technology for actuation. Ayers, for example, developed a myomorphic actuator for his robotic lobster exploiting SMA wires and using pulse width duty cycle modulation to grade the proportion of martensite that transforms to austenite [28].

1.2.1.4 Shape memory polymers

Shape memory polymers (SMPs) belong to a class of smart polymers, which have drawn considerable research interest in the last few years because of their applications in micro electromechanical systems, actuators, for self-healing and health monitoring purposes, and in biomedical devices. Shape memory polymers exploit the same idea as SMAs: the configuration at the point of cross-linking in a polymer network is the lowest energy configuration. Any deformation away from that configuration increases the energy. Thus, by stretching the rubber at a temperature above the crystallization point and then cooling it in that extended shape will lock-in the deformed material. On heating to melt the crystals, the original network configuration is recovered. A variety of materials have been employed. Like in other fields of applications, SMP materials have been proved to be suitable substitutes to metallic ones because of their flexibility, biocompatibility, and wide scope of modifications. The shape memory properties of SMPs polymers might surpass those of shape memory metallic alloys (SMAs). A comprehensive review can be found in [29].

1.2.1.5 Flexible fluidic actuator

Flexible fluidic actuator is a term for a wide range of system types, but generically flexible fluidic actuators comprise an expansion chamber defined by an inner wall of an expandable girdle, the expandable girdle being connected to at least two anchoring points. The expansion chamber has at least one fluid inlet to allow pressurized fluid into the chamber. The expansion chamber is capable of acquiring a minimum volume and a maximum volume. Thus, these flexible actuators are able to adapt and transform a fluid pressure force against the inner wall of the expandable girdle and so produce a traction force or a bending movement among the two anchoring points, when the expansion chamber is inflated by the pressurized fluid entering through the fluid inlet.

1.2.2 Discussion and Choice of Active Motion Technology

The fluidic actuation presents nice features regarding an application inside the human body [30] (see table 1.1). Indeed, it has the non-negligible advantage to prevent having energized parts, i.e., being under electrical voltage (unlike electrostatic actuators, piezoelectric actuators [31], electroactive polymers, or electromagnetic motors when used inside the body), or high-temperature parts (unlike the SMA and thermal actuators) inside a patient's body; this increases safety. As no electrical power is used, operation in the presence of radioactivity or magnetic fields is possible [32]. In the case of a hydraulic

Table 1.1 Comparison table of several candidate technologies for the active motion of the module: red–unacceptable; light red–undesired; light green–acceptable; and green–desired

	input energy domain	scaling of dimensions	hard/soft type	Strain (%)	stress max (MPa)	power (W/cm^3)	Response time	Bandwidth (Hz)	Max strain rate (%/s)	Efficiency (%)
motor-driven	electric	limited	hard	0.5	0.1	0.1	fast	20	>1000	>80
SMA driven	electric and thermal	high	soft	0.1	200	0.35	medium-slow	3	100	3
Electroactive polymers	electric and thermal	high	soft	0.5	0.3	0.75	medium-slow	10	NA	30
Piezoelectric actuation	electric	high	hard	0.002	35	175	fast	5000	>1000	50
magnetostrictive actuators	magnetic	medium-high	soft	0.002	35	70	medium-slow	2000	NA	80
Electrostrictive polymer actuated muscles	electric	medium-high	soft	0.5	0.3	0.75	medium-fast	10	NA	30
Hydraulic actuators based	Fluid	medium-high	medium soft	0.5	20	20	medium-fast	4	100	80
Pneumatic actuators based	gas	medium-high	soft	0.5	0.7	3.5	fast	20	70	90

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 because small variations of the shape or size of the components (seal, seal house, or piston) involve high friction or leakage. De Volder et al. [33] propose 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, pressurized elastic deformable chambers are preferred to be used, i.e., flexible fluidic actuators, as suggested by Suzumori et al. [34].

As these actuators present no relative motion of parts, static sealing 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 [35]. Besides, smooth motion and precise positioning are possible to achieve since there is no friction [34] (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:

1. They can handle delicate objects without causing any damage thanks to their inherent compliance [35]. This compliance allows them to adapt themselves to their environment during contacts [35, 36].
2. 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 [37]. This is an interesting feature regarding miniaturization.
3. 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**:

1. Regarding a medical application, reducing the fluid pressure, the device loses its rigidity and recovers its initial shape. In emergency cases, it

offers the opportunity to take the instrument out of the patient's body quickly.

2. Devices based on this principle and whose actuation is obtained by the deformation of elastic chambers have the intrinsic and very useful property of giving to the operator a reliable feedback about their posture and actuation force by measuring the volume and pressure of the operating fluid that has been supplied.

Nevertheless, fluidic actuation comes with some **drawbacks**:

1. Fluidic actuation 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.
2. Regarding fluidic micro-actuators: the pipes used to drive the fluid can present leakages and cause pressure losses that limit efficiency [38]. Moreover, controlling fluid pressures and flow rates in small sections is often more delicate than controlling electrical quantities.
3. Another shortcoming of flexible fluidic actuators is due to the required control as explained in [35]: Fluidic flexible robots require sophisticated controllers in order to reach accurate and repeatable positioning. Moreover, the deformable structure and non-conventional actuation make their dynamics modeling very complex.

Finally, regarding the fluids used to inflate these actuators, one has characteristics that compensate the lacks of the other and vice versa. Liquids can generate higher forces and, in general, their supply circuit is safer since it has reduced possibilities of explosions when compared with gases. In addition, the compressibility of gases brings about more compliance, so that it leads to a more difficult characterization and modeling since it also involves thermal losses upon compression. On the other hand, air is a readily available source and exhaust gases (i.e., air) can be freely evacuated in the environment [39]. Furthermore, gases lead to more lightweight actuators and to pressure losses 1,000 times smaller than those for liquids [40].

1.2.3 Stiffness Variation Technology Survey

The technological solutions considered for the realization of the stiffness variation of the STIFF-FLOP manipulator are reported in this section. The survey is followed by a comparison table that guides the choice of the most suitable technology.

Stiffness variation is one of the main features of the STIFF-FLOP arm. The arm should be able to safely interact with the surgical environment adapting its stiffness according to the situation and the surgical task. Indeed the arm should be able to navigate in the body cavities in a floppy state and then selectively stiffen some of its segments to actively move organs or accomplish surgical tasks. Generally, navigation in the body cavities is performed using flexible medical instruments such as conventional endoscopes. These instruments are used because of their high flexibility, which enables traversing tortuous trajectories and the reaching of many different surgical targets, possibly even without the need to make skin incisions. Novel surgical instrumentation is being developed in order to exploit the higher dexterity, flexibility, and potential for miniaturization of these instruments. Many prototypes for robotic surgery and endoscopy have been developed and commercialized [41–43]. Typically such flexible instruments are composed by a flexible "backbone" or springs [44] and are actuated by motors located externally. The flexible backbone causes them to have low stiffness and makes it difficult to control the rigidity [45].

The stiffness variation in endoscopic instruments has been widely investigated [46]. Various stiffening strategies have been developed and have been considered in the choice of the STIFF-FLOP arm stiffening mechanism. Following the approach described in [46], both rigidity controls based on material stiffening and structural stiffening have been considered and reviewed. Rigidity control based on material stiffening exploits the change in the mechanical properties on particular materials due to controlled physical stimuli. Examples are phase change of **thermoplastic polymers** [47–53]. Phase change induced by temperature change can be used to change the stiffness of thermoplastic polymers from values resembling low viscosity fluids to values resembling rigid nylon. The main drawbacks of phase change polymers are that they are difficult to control and have low response time slow (order of second) since they rely on heating and cooling systems.

Other materials that can be used for stiffening varying their mechanical properties are electro and magneto rheological fluids. Electrorheological fluids change their viscosity in response to an electric field. They have been proposed for different applications [54, 55]. However, this kind of fluid requires high electric field, for example, in [56] and [57], it is reported that in this case, an electric field up to 5,000 V/mm at 2–15 mA/cm^2 is required to obtain yielding strength change from about 0 to 5 kPa, turning from liquid to quasi-solid in few milliseconds. Magnetorheological fluids work in a similar way to the electrorheological ones but they respond to a magnetic field. Although they are more energy efficient than electrorheological fluids [56, 57], they need high magnetic field (239 kA/m) for rigidifying a device (maximum yielding strength of 100 kPa). Such field would require highly encumbering magnetic sources.

Rigidity control based on material stiffening can be useful for precise control of damping and is mostly used in active damping mechanisms (tunable automotive suspensions), not for drastic changes in elastic modulus as required for robotic applications. As described above, sole material stiffening would not fit the stiffening requirements of the STIFF-FLOP arm.

Stiffening of a flexible structure can be obtained by locking the relative movements between interconnected parts of a structure (structural stiffening). As shown in Table 1.2, structural stiffening can act both on the angle of each successive segment of a flexible backbone (angle locking) and on the lengths of the inner and outer curves of the bends in a shaft-guide that are locked (curve length locking).

Both angle locking and curve length locking can be discrete or continuum. The discrete angle is mainly based on the increase in friction between two consequent joints due to the tensioning of the structure by means of cables or other tensioning systems. Applications can be found in [58–65].

In the discrete curve length locking strategy, the distance between the outer edges of succeeding elements is fixed [66] by means of cables, fluid columns, rods, or any other element that can lock and unlock the distance between two points.

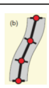
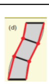
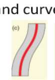
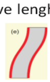
Both discrete curve length locking and angle locking mechanisms require relatively large amounts of mechanical components and therefore are not simple to produce or scale down. In addition, since they mainly rely on friction between two or more components, stiffening control in not much controllable; indeed, they are mainly used as on–off mechanisms. In the case of continuum structural stiffening, the stiffness variation occurs continuously along a structure, not only between two or more segments. This kind of stiffening can be used both for angle locking and for curve length locking. Recently, Loeve et al. [67] presented a continuum structural stiffening strategy based on friction between a central fluidic channel and the cable actuation mechanism. Otherwise, it can be implemented by exploiting vacuum packed particles [68–74].

This strategy is based on the physical phenomenon of **granular jamming**. Granular jamming is a growing field in robotics, and is a mechanism which enables particles to act like a liquid, solid, or something in between depending on an applied pressure. As stated by [75], jamming is a phenomenon where an external stress can change “fragile matter” from a fluid-like to a solid-like state. Because of this unique feature, many groups have integrated granular jamming into robotic projects such as the universal robotic gripper [76], the tendon-supported elephant trunk, the jamming skin-enabled locomotion robot [77, 78], the variable stiffness haptic device [79], the variable stiffness endoscope [46], and the emergency vacuum splint [80].

1.2.4 Comparison and Choice

Granule or particle jamming has interesting features such as high deformability in the fluid state, and drastic stiffness increase in the solid state, without significant change in volume; in addition, it allows controlling the stiffness level by controlling the level of an applied vacuum (see table 1.2). Due to these unique features, it is currently the design choice explored for the stiffening mechanism of the STIFF-FLOP arm. Indeed, it is the most suitable solution for highly deformable soft structures.

Table 1.2 Comparison table of several candidate technologies for the variation of the module stiffness: red–unacceptable; light red–undesired; light green–acceptable; and green–desired

Stiffening Strategy		***Physical phenomenon involved***	***Controllability***	***Responce time***	***Stiffening range***
Material stiffening 	Phase change polymers	**phase change** of thermoplastic polymers	**Low**	order of **second**	From **low viscosity fluids** to values resembling **rigid nylon**
	Magnetorehology	changes their viscosity in response to **magnetic field**	**Low** (difficoult to tune stiffness)	**millisecond**	maximum yielding strength of 100kPa (239 kA/m magnetic field)
	Electrorehology	changes their viscosity in response to **electric field**	**Low** (difficoult to tune stiffness)	**millisecond**	**yielding strength change from about 0 to 5 kPa** (5,000 V/mm at 2–15 mA/cm²)
Structural stiffening	Descrete Angle locking 	**Friction** between two consequent joints due to the tensioning of the structure	**Low**, mainly on-off	High	**Shapelocking** capabilities applying high tensioning forces
	Descrete Curve lenght locking 	the distance between the outer edges of succeeding elements is fixed by **friction**	**Low**, mainly on-off	High	**Shapelocking** capabilities applying high tensioning forces
	Continous angle locking and curve lenght locking  	This strategy is based on the physical phenomenon of the **granular jamming.**	**Possible** controlling the vacuum level	**High, dependent** on performances of the **vacuuming system**	high deformability in the fluid state, and **drastic stiffness increase in the solid state**

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