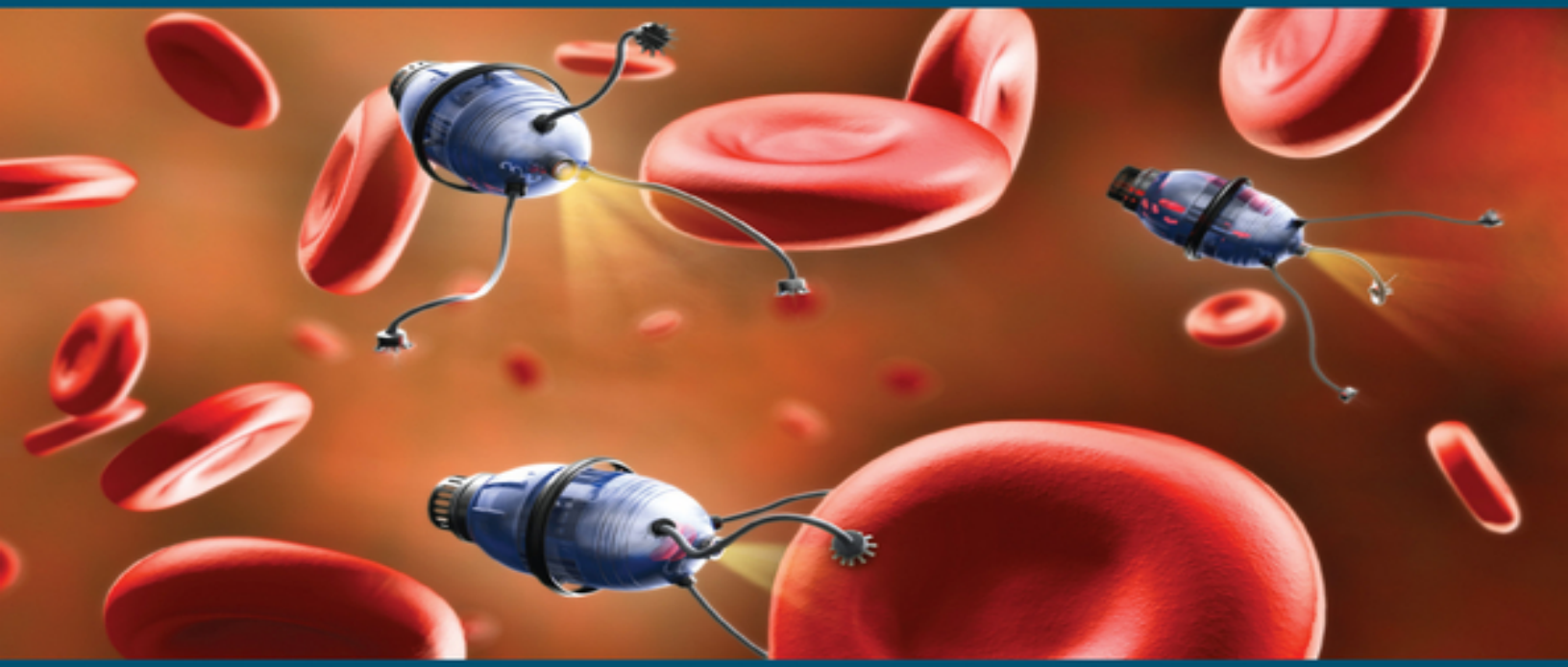
ROBOTICS SERIES



Intracorporeal Robotics

From Milliscale to Nanoscale

Michaël Gauthier
Nicolas Andreff and Etienne Dombre

ISTE WILEY

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Introduction

For almost 30 years, research in medical robotics has led to many prototypes that have been validated technically, and some clinically. There are many specialties in this regard. Orthopedics, neurosurgery, endoscopic microsurgery (mainly gynecology, urology, fetal surgery, etc.), cardiac, thoracic and vascular surgery, ear, nose and throat (ENT) surgery, etc., are a few among others.

It is clear that robotics may facilitate surgical approaches such as minimally invasive surgery (MIS), natural orifice transluminal endoscopic surgery (NOTES), single port access (SPA) surgery and interventional radiology, and it is very promising in microsurgery. We list in Table I.1 some benefits for the patient and the surgeon of robots in the operating room (OR). To summarize, surgical robotics may contribute to less invasive and more accurate surgical gestures. It may also be useful in transcending human limitations.

Considering the benefits, it is surprising that only a few prototypes have managed to find their way into OR or medical offices. Several reasons are generally raised of which a few of the most important are given below:

– The cost issue: the cost effectiveness of robotic systems has not yet been proved. Several factors worked against it: the cost of the OR is increased; a technical team is required; the surgical team has to be trained; the setup and ‘skin-to-skin’ times are longer than conventional procedure. The compatibility with the cluttered environment of the OR should also be improved: the robots are still too bulky; quite often, the weight, dimension and footprint of the robot are out of proportion with respect to the force it has to exert and the workspace it has to cover during an operation.

– The clinical added value: as noted in the report of the IARP Workshop on Medical Robotics[1], the medical added value has to be improved: *Medical robotics suffers from a "chicken and egg" phenomenon in the sense that systems need to be developed before they can be tested clinically, but only through the latter will their true effectiveness and utility be proven […]*.

– Safety issues: a medical robot is a complex system that consists of (1) an articulated and motorized mechanical structure, (2) a human–machine interface, (3) electronic components and (4) a software controller. These components are used to perform operations in a constrained and not fully structured environment, inside and/or outside of the patient's body, in cooperation with the surgeon, and in the presence of the medical staff. Thus, it is easy to understand that a system failure or dysfunction can be extremely critical [SAN 13b].

This analysis pushes for the development of a new generation of robotic systems along three major challenges [DOM 12b]:

– Cost: they will be less bulky and less expensive than the current systems.

– Ergonomics: they will be of *plug and* play-type like most tools and equipment in the OR in order to minimize the installation time. They will also be easy to use in order not to require special technical skills of the staff. Moreover, the sensors will be sterilizable, otherwise disposable, and highly integrated into the architecture of these systems.

– Safety and medical added value: they will be increasingly less invasive and will not significantly extend the duration of the intervention. Moreover, the doctor/robot interfaces will be specifically designed to facilitate the implementation while ensuring that the level of operational safety is as high as possible.

Table I.1. *Medical robots: benefits for the surgeons and patients*

Fields of application	Potential benefits to the surgeon	Potential benefits to the patient
– Orthopedic surgery	– ↗ Precision – Possibility of carrying out complex cutting, drilling, milling – Integration of multimodal preoperative and intraoperative information (vision, force) – ↗ safety (virtual fixture)	– Less revision surgery – Expected longer lifetime of prostheses
– Minimally invasive endoscopic surgery	– 3rd hand – Greater comfort – Elimination of the fulcrum effect – Additional internal mobilities – Compensation of physiological movements	– Toward an increasingly less invasive surgery and without visible scars
– Neurosurgery – Interventional radiology – Radiotherapy	– ↗ Precision – ↗ Safety (avoidance of vital structures) – Compensation of physiological movements – ↘ Exposure to radiations – Precise spatial tracking of the dosimetric planning	– ↘ Invasiveness – Early treatment of increasingly smaller tumors – ↘ Exposure to radiations of healthy tissues
– Microsurgery	– Downscaling of the forces and displacements – Surgeon's tremor filtering	– Development of innovative procedures beyond the accuracy limits of the surgeon

The above specifications (cost, ergonomics and safety) imply that the future surgical robots should be smaller and dedicated to a limited number of functionalities with a certain level of autonomy appropriate for the complexity of the task they are supposed to achieve. In any case, the surgeon must maintain control of the gesture no matter what, at any time of the operative or exploratory procedure. From this observation, we understand that for many surgical applications, it makes sense to integrate the mobilities and the sensors inside the body rather than outside. In other words, rather than manipulating a multimillennial rigid

instrument (like scissors or clamps) with an extracorporeal robot, the idea is to develop intracorporeal robots, offering at least the same performance of movement quality, safety and interaction with the doctor.

Surgical robotics raises several ethical issues that should be addressed very early in the design process. Some of them are covered by regulations already applicable in the pharmaceutical and medical equipment industry. For intracorporeal robotics, specific issues arising from miniaturization should also be addressed, but they have not yet received the attention they require. The IEEE Robotics and Automation Society[2] has launched a Technical Committee on Roboethics[3] to provide a "framework for taking care of ethical implications of robotics research". A biannual workshop dedicated to the subject has been organized in conjunction with the IEEE International Conference on Robotics and Automation (ICRA) from 2005 to 2011. A Workshop on Legal, Economic and Socio-Ethical Implications for the Next Generation of Robots[4] was held at ICRA 2013. It was organized by the partners of the FP7 project RoboLaw[5]. One can also refer to the pioneering initiative of G. Veruggio[6] in the framework of the European Robotics Research Network (EURON) and the work of R.C. Arkin[7] at Georgia Tech as other entry points to the subject.

Crossing the border of the skin opens up new clinical horizons but requires overcoming several technical barriers. These barriers depend on the size of the biological objects to be manipulated: organs, tissues, cells and internal components of cells. The latter are at nanoscale while the cell size is mostly below 100 µm and usually around 5 to 10 µm. The physical principles that describe the behavior of the objects are different according to their size: the dynamics of large micro-objects (e.g. 100 µm) is limited by inertia while the dynamics of smaller objects (e.g. 1 µm) is limited by

viscosity. It is then convenient to divide the world into the following groups:

– The macroworld is dominated by volume effects (inertia and weight).

– In the microworld, volume effects (dielectrophoresis and magnetophoresis), surface effects (van der Waals' force) and linear effects (viscous force) are balanced.

– The nanoworld is dominated by surface effects and linear effects.

In this book, we will consider four scales of object sizes, which are justified by the class of problems encountered and the solutions implemented to manipulate objects and reach targets within the body (note that the size of the object has no evident relation to the size of the device that manipulates it):

– At milliscale (Chapter 1), the dimensions of the objects range from a few millimeters to a few centimeters, and the forces required to manipulate tissues range from a few millinewtons to several newtons. Most of the robotic systems at this scale use the manipulation principles of the macroworld.

– At microscale (Chapter 2), comprising objects below 1 mm up to 10 µm, the forces are in the order of tens of nanonewtons up to a few millinewtons. Original manipulation principles under magnetic field or by swimming in a liquid media have been validated.

– At mesoscale (Chapter 3), between 100 nm and 10 µm, the forces range from piconewtons to tens of nanonewtons. We have introduced this term to designate a scale where the contact with any tool could destroy the object, which requires implementing non-contact manipulation principles.

– At nanoscale (Chapter 4), between 1 nm and 100 nm, the manipulation of objects is still a challenge that will require a paradigm change. As will be discussed, progress will depend on multidisciplinary research bringing together

biology, chemistry, robotics and, more widely, engineering sciences.

The book reviews the physical principles as well as the scientific and methodological challenges that have to be tackled to design and control intracorporeal robotic systems at each of the above-mentioned scales. The most prominent devices and prototypes of the state of the art are described in the first three chapters to illustrate the benefit that can be expected for surgeons and patients. In Chapter 4, we will discuss perspectives on nanorobotics.

To conclude this Introduction, let us recall that a robot is defined as *"an actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks"* (ISO 8373:2012 document). Devices that use robotic or mechatronic technologies or components found in robots but unable to carry out autonomous motion should be referred to differently (e.g. robotic system, robotic manipulator and robotic positioner). For the sake of simplicity, the term "robot" will be used more widely for any programmed, teleoperated or comanipulated device.

1 http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshop Report.htm.

2 http://www.ieee-ras.org/.

3 http://www.ieee-ras.org/robot-ethics.

4 http://www.robolaw.eu/ws_icra2013.htm.

5 http://www.robolaw.eu/index.htm.

6 http://www.veruggio.it/.

7 http://www.cc.gatech.edu/aimosaic/faculty/arkin/.

Chapter 1

Intracorporeal Millirobotics

1.1. Introduction

Intracorporeal millirobots are at the boundary of conventional surgical robots that are installed in the operating room (OR) along the table or on the patient. They still work in the macroworld, where volumic forces and torques (such as weight) dominate. Under this designation, we mean devices with either partially or fully intracorporeal actuated degrees of freedom (DoFs). Their dimensions in the body can reach at the maximum a few tens of millimeters. The dimensions of the surgical site range from a few millimeters to a few centimeters; however, when it is mobile, the millirobot may cover a workspace of several cubic centimeters. The forces exerted on tissues by the robot range from a few millinewtons to several newtons, up to tens of newtons for retraction of organs or gripping a needle.

At this scale, many prototypes have been developed, even though very few of them have entered the OR. In many cases, they look like conventional robots for which rigid body kinematic models and vision-based or force-based control algorithms may be used. More or less, they could be seen as miniaturized versions of existing solutions.

However, to comply with the environment constraints (biological tissues, safety, etc.) and the task constraints (access to deep anatomical spaces, preservation of vital structures, high dexterity, etc.), many efforts have been

made to design original kinematics with advanced sensing capabilities for manipulation and locomotion purposes. A promising approach is now to integrate robotics in instruments rather than to think of the robot as a simple instrument holder.

In section 1.2, we will present a variety of millimetric devices providing intracorporeal manipulation and/or mobility capabilities. In section 1.3, we will address scientific issues that are specific to robotics at milliscale. These issues cover the main fields of robotic research in modeling, design, actuation, sensing and control. In section 1.4, we will present in more detail three robotic systems that are representative of the state of the art at the milliscale: a dual-arm master–slave system, a snake-like robot made up of concentric tubes and a handheld robotized instrument.

1.2. Principles

We present in this section the principles of three classes of devices:

– partially intracorporeal devices with active distal mobilities;

– intracorporeal manipulators;

– intracorporeal mobile devices.

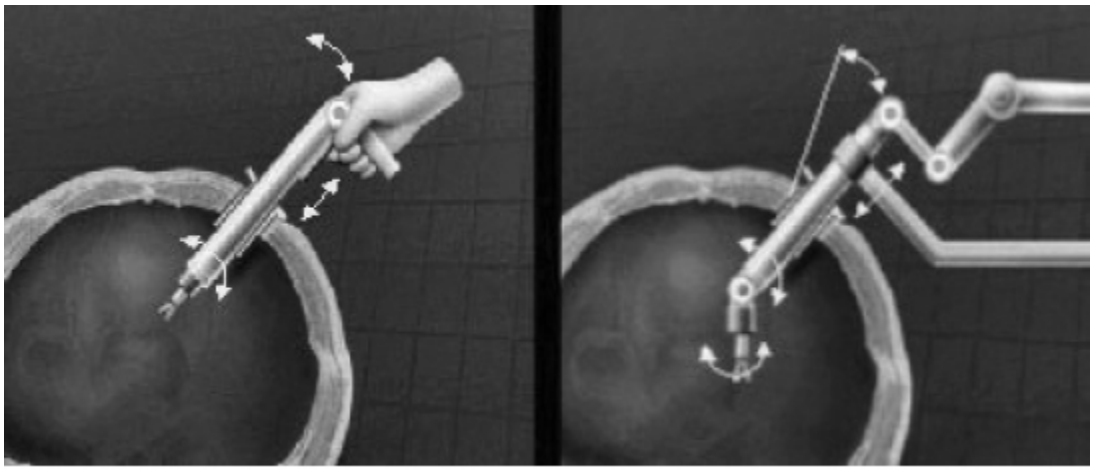
Their purpose is functional exploration (in the case of capsules) as well as intervention (to remove a polyp, place a stent, deliver a drug in a localized manner, etc., but also cut, retract, dissect and cauterize as in conventional surgery). Emphasis has been put on several representative devices of each class to review functional qualities and limits of potential robotic solutions. A more comprehensive review of many prototypes worldwide can be found in [DOM 12b].

1.2.1. *Partially intracorporeal devices with active distal mobilities*

Under this denomination, we mean conventional instruments that have been modified to improve dexterity and/or precision of the surgeon or the radiologist. We include, for instance, any device providing two additional actuated DoFs between the entry port in the body and the tool (retractor, forceps, needle driver, but also tip of an endoscope), not accounting for the closing/opening of the jaws of the tool if any. The partially intracorporeal device is generally attached to an external device that can be a robot providing supplementary DoFs. It is driven externally by the surgeon, either directly in a comanipulation mode (section 1.3.5.3) or from a master workstation in a teleoperation mode (section 1.3.5.2) (Figure 1.1).

With such a definition, we consider entering into this class the actuated instruments for endoscopic surgery and the catheters. Typically, the diameter of these instruments is restricted to 8–10 mm in abdominal surgery, 5–6 mm in cardiac surgery, even 2.5–3 mm for intrauterine fetal surgery [HAR 05, ZHA 09a], 0.5–2 mm for an active catheter.

Figure 1.1. *Partially intracorporeal DoFs: a) comanipulated instrument; b) teleoperated instrument [SAL 04]*



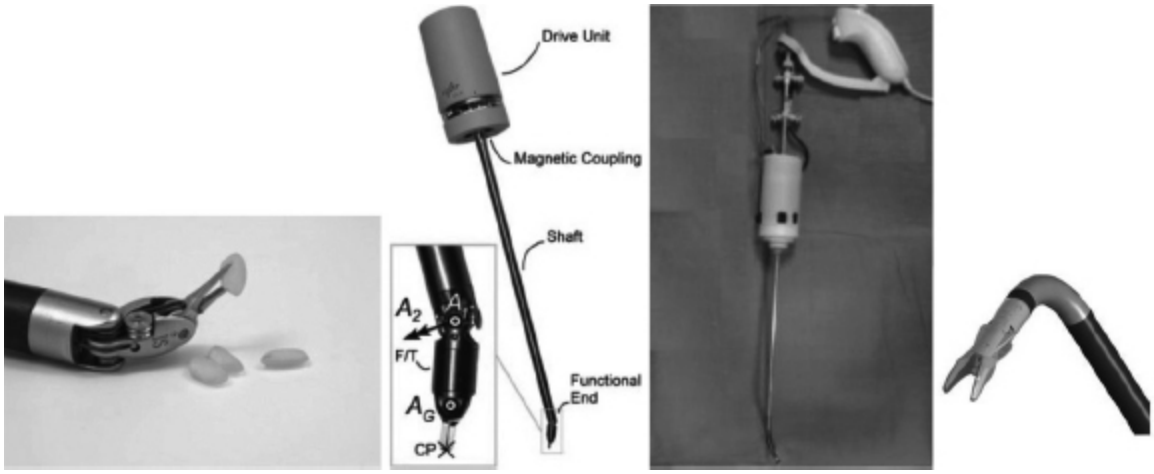
a) b)

1.2.1.1. *Actuated instruments for endoscopic surgery*

As opposed to open surgery, endoscopic surgery has revolutionized surgical practice since the early 1970s. Often referred to as minimally invasive surgery (MIS), it reduces postsurgery wounds, the risk of infection, the recovery time and the cost of treatment. But it suffers from a certain number of shortcomings: loss of internal mobility due to kinematic constraints induced by the trocar, hand–eye coordination due to the inversion of directions of motion of the hands and the tool tip, loss of force and tactile feedback, restricted workspace and surgeon's fatigue. These limitations have motivated the development and introduction of robots in the OR. Since the mid-1990s, with the robotic systems ZEUS (Computer Motion[1]) and Da Vinci (Intuitive Surgical[2]), master–slave architecture has been adopted for MIS: the instruments are carried by two or three slave manipulators teleoperated by the surgeon from a remote master console. Along the same lines, it is worth mentioning the platforms Raven II from University of Washington [HAN 13] and MiroSurge from DLR [HAG 10] that are dedicated to research in robotic surgery.

In these systems, the active part of each instrument may have up to two actuated DoFs (not including actuation of the gripper) mounted at the distal end of a rigid hollow tube through which the driving cables pass (Figure 1.2, left). Such additional DoFs may also be mounted at the distal part of a lightweight handheld system (Figure 1.2, right) that gives the surgeon the ability to comanipulate the instrument without using a master arm [ZAH 10]. In both cases, the additional pan and tilt rotations compensate for the loss of mobility induced by the constraint of passage through the trocar.

Figure 1.2. *From left to right: close-up of the Da Vinci Endowrist tip manipulating rice grains; DLR MICA instrument of the MIRO platform for endoscopic surgery and close-up of the two-DoF wrist mounted with a force/torque (FT) sensor [HAG 10]; the EndoControl[3] handheld laparoscopic instrument JAiMY [ZAH 10]; close-up of the two-DoF bending and rotary wrist of JAiMY*



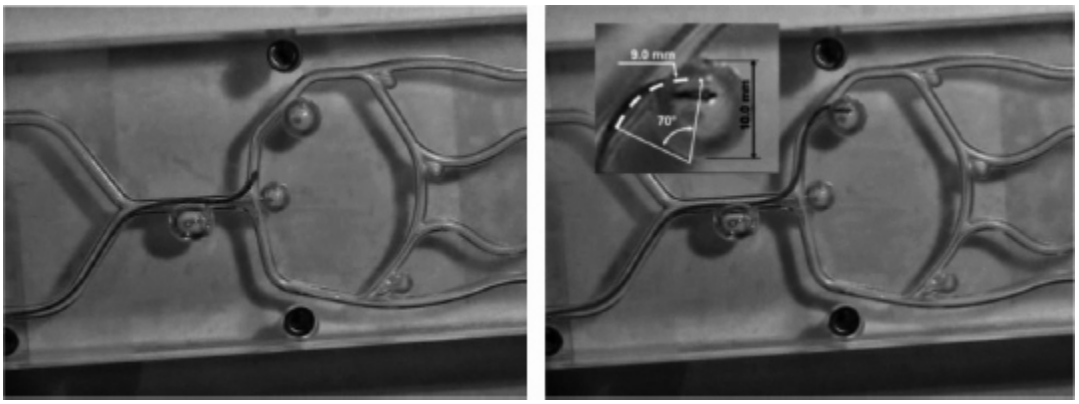
1.2.1.2. *Actuated catheters*

A catheter is a thin (a few millimeter in diameter), long (of the order of a meter) and hollow tube that allows the passage of functional catheters of smaller diameter. These may hold various miniature sensors (pressure, ultrasound

probe, optical fiber, etc.) or instruments, e.g. for the local administration of a drug, the insertion of a prosthesis (stent, angioplasty balloon, etc.), the endovascular coiling of aneurysms, the puncture/biopsy for diagnostic purposes or tumor destruction (radiofrequency abalation, laser therapy, etc.) [CHA 00]. The catheter is inserted into an artery, usually in the groin. It is steered, under radiographic control, by the doctor who rotates it around its longitudinal axis and pushes it to its destination. This is made difficult because of the narrowness of the vessel, the frictions on the wall and the many bifurcations. The difficulty for the surgeon is thus to transmit force and motion to the end effector with little or no relevant kinesthetic feedback, and with a restricted and sparse visual feedback to limit the radiation doses, while avoiding perforation of the artery.

An active catheter is shown in Figure 1.3 [SZE 11]. It is endowed with guidance abilities to facilitate its introduction in bifurcations that exhibit restrictive directions (including very acute closed angles). There are some similarities between an active catheter and a teleoperated robotized colonoscope, however, the diameter is nearly one order of magnitude lower, typically 1–2 mm (the diameter can be reduced to 0.5–1 mm in the case of a guidance catheter). The other difference, and the major difficulty, is that the catheter must move in an artery where the pressure and the blood flow are important. Many prototypes of active catheters have been developed over the last 10 years where many actuation concepts have been explored as will be presented in section 1.3.3.

Figure 1.3. *Navigation of an active catheter in a phantom of an aneurysm in the Willis Polygon (Ø = 1.1 mm, radius of curvature = 9 mm) [SZE 11]*



To protect the surgeon against radiation, master–slave systems, which allow the doctor to remotely control the catheter, are now available, such as the Sensei X Robotic System, and more recently the Magellan Robotic System, both marketed by Hansen Medical[4], or the Amigo RSC from Catheter Robotics[5]. These systems offer a steering unit that pushes and allows bidirectional rotations of the catheter tip.

1.2.2. *Intracorporeal manipulators*

We give the name intracorporeal manipulators to any device providing full (or at least more than 2) mobility to the tool with actuated DoFs located between the entry port in the body and the tool. These devices may be minimanipulators (scaled version of conventional robot arms) or flexible instruments designed to perform new techniques of surgery without visible scaring. We also include in this class modular approaches aiming at assembling and disassembling (or possibly deploying and retracting) robots and platforms within the body.

1.2.2.1. *Minimanipulators*

Typically, minimanipulators have a centimetric size, generating submillimetric to centimetric displacements and

can exert forces of the order from 1 N (e.g. to insert a needle into a coronary artery) to several tens of newtons to retract tissue. Different options may be adopted in the design:

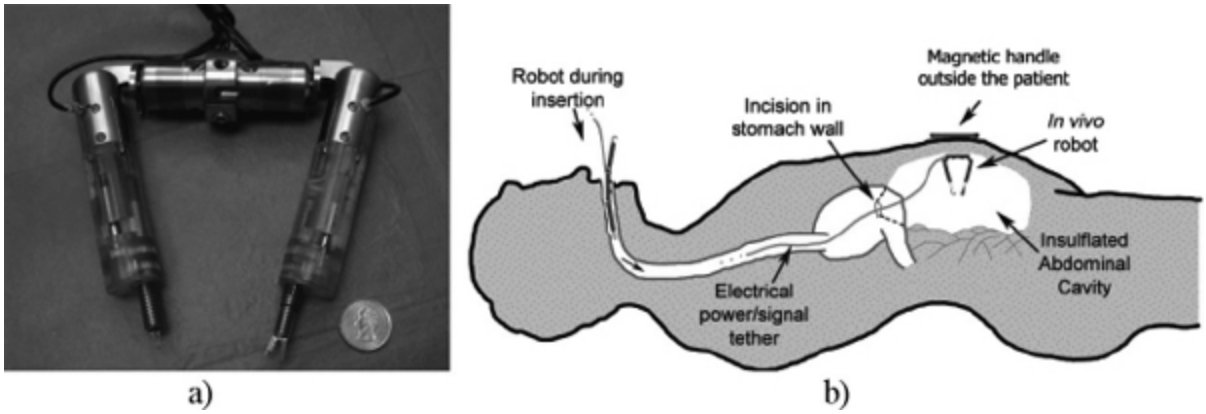
– discrete architectures with embedded actuators;

– discrete architectures with remote actuators (outside the patient);

– continuum architectures (or snake-like or elephant trunk like architectures) with remote actuators.

Discrete architectures have a limited number of rigid links and discrete joints. A first example of such robot with embedded actuators, designed for *natural orifice transluminal endoscopic surgery* (NOTES) (section 1.2.2.2), is shown in Figure 1.4 [LEH 08, TIW 10]: it consists of two prismatic arms each connected to a central body by a revolute joint, together providing four planar DoFs. Each arm is fitted with either a grasper forceps or a cautery end effector. The central body contains a stereo camera pair and magnets that interact with external magnets to attach the robot to the interior abdominal wall. It is inserted through the esophagus and into the peritoneal cavity using an overtube in a configuration where the arms are disconnected from the central body.

Figure 1.4. *a) In vivo two-arm dexterous robot from Vanderbilt University; b) NOTES procedure [LEH 08, TIW 10]*



Another example is the modular robot DRIMIS [SAL 04] (Figure 1.5(a)), which is the result of an optimization procedure using multiobjective evolutionary algorithms, coupled with a realistic simulation of the intended surgical task (anastomosis during coronary artery bypass grafting). Several one-DoF and two-DoF modules (Ø 10 mm, 25–40 mm long) were designed with different axis organization. Typically, a six-DoF arm is 120 mm long.

The arms of the dual-arm robot SPRINT have a similar kinematics. The platform was developed in the frame of the EU FP7 Araknes project[6] [PIC 10, SAN 11] (Figure 1.5(b)). Each arm has six DoFs plus the gripper. Four additional DoFs are provided by the external positioning device. In its current version, the size is 18 mm in diameter and 120 mm in length. It can exert forces up to 5 N. The robot is intended to be attached to the umbilical access port in *single-port access* (SPA) surgery (see section 1.2.2.2). A detailed description of the system is presented in section 1.4.1.

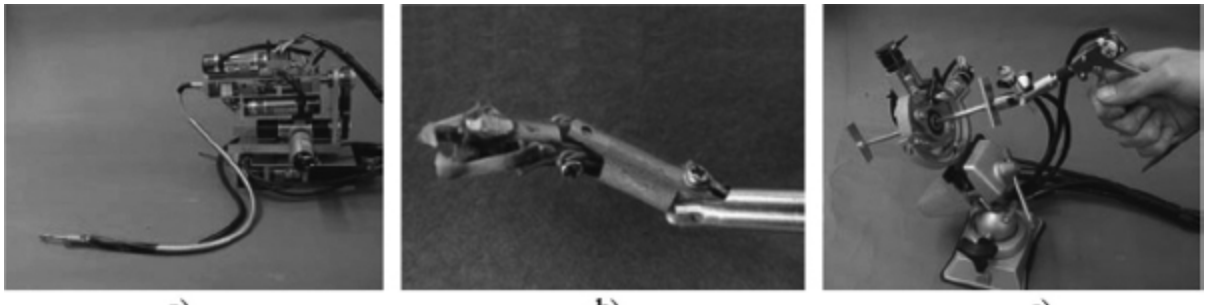
Figure 1.5. *Architectures with rigid links and discrete joints: a) DRIMIS (ISIR) [SAL 04]; b) SPRINT (Araknes project) [PIC 10, SAN 11]*

When miniature actuators are embedded in the structure, one of the difficulties is the routing of the electrical cables, another is the small power-to-weight ratio of the actuators available at this size, dramatically restricting the forces that can be exerted by the robot on tissues. The latter no longer

holds with remote actuators. However, remote actuation implies using mechanical wires to drive the joint, which is a more tricky issue than routing electrical cables. An example of such an architecture designed by Ikuta *et al.* [IKU 03] is depicted in Figure 1.6: the Hyper Finger (Mark-3) is a seven-DoF (including the forceps griping action) wire-driven active forceps for laparoscopic surgery (Ø 10 mm). A special decoupled two-DoF "ring-joint" mechanism was developed, where each DoF can be driven independently. It is teleoperated with an analogous seven-DoF master finger.

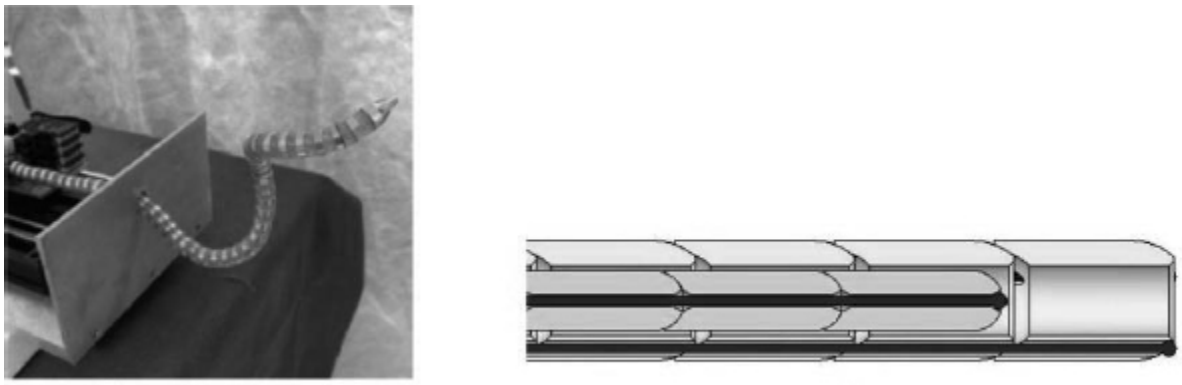
An interesting alternative to the discrete aforementioned minimanipulators is the continuum robots. They have a smaller outer diameter with comparable performance specifications [XU 12]. They more or less extend the design used for bending the tip of active catheters. The actuators are placed outside the patient, pulling cables or "tendons" of different technologies to control distributed stiffness and curvature, as will be discussed in section 1.3.3. Zhang *et al.* [ZHA 11] have designed a six-DoF wire-driven robotic manipulator for fetal surgery, namely to place a detachable silicone balloon in the fetal trachea for treatment of congenital diaphragmatic hernias. The robot is constituted of three units, each having two DoFs. The size is 2.4 mm in diameter. The contact force of the robot is controlled to be less than 0.3 N.

Figure 1.6. *Hyper Finger [IKU 03]: a) seven-DoF slave manipulator at the end of a guide tube; b) close-up of the seven-DoF manipulator; c) master manipulator*



To navigate in a constrained operating workspace, circumventing vital organs and risky areas, a higher number of DoFs is required. HARP (highly articulated robotic probe) is a continuum and hyper-redundant robot proposed by [DEG 06, OTA 08] for pericardial interventions. It is made up of two snake-like concentric tubes (Figure 1.7) that can maintain the three-dimensional (3D) shape of the path they follow: each snake can be rigid or limp, and HARP progresses forward by alternating the rigidity/limpness of both snakes. Each snake consists of 50 rigid cylindrical links articulated by spherical joints (±15° in both directions) and strung together by cables (four for HARP). It is 12 mm in diameter, 300 mm in length and can achieve a 75 mm radius of curvature (reduced to 35 mm in a later version). The flexibility of each tube varies according to the tension of the cables. This technological approach is now integrated into the robot-assisted platform of Medrobotics[7].

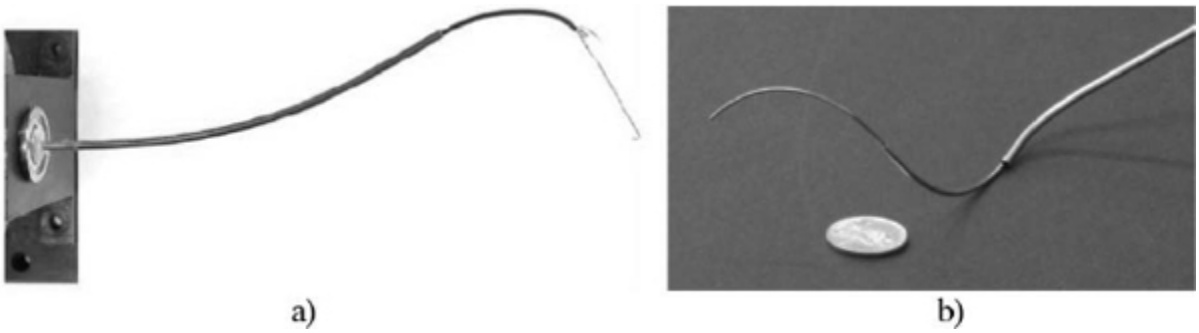
Figure 1.7. *Continuum architecture: a) HARP [OTA 08]; b) side cross-sectional view of the two concentric snakes [DEG 06]*



An interesting concept, proposed by Dupont [SEA 06] and Webster [WEB 06a], consists of several pre-bent concentric hollow tubes made up of a super-elastic material such as Nitinol (Nickel Titanium alloy also referred to as NiTi). The resulting snake-like robot (Figure 1.8) may deform

continuously by independently translating and/or rotating each tube with respect to the tube in which it is inserted. It has several advantages: it is lightweight; it can be customized in diameter and length to meet the requirements of the operation at hand; it has a very good dexterity and can be deployed while avoiding vital structures; knowing its stiffness makes it possible to evaluate the interaction forces with tissues. We will discuss more in detail design and modeling issues associated with such a robot in section 1.4.2.

Figure 1.8. *a) Prototype of a miniature concentric tube robot of Boston University grasping a needle [SEA 06];b) prototype of JHU [WEB 06a]*



1.2.2.2. *NOTES and SPA devices*

Two new paradigms of surgery are currently being developed within the field of MIS: the transluminal surgery, also known as NOTES [JAG 05, PAR 05], and the surgery through single trocar or single incision [PIS 99, DAL 02], also known as SPA surgery. The common point of these techniques is the absence of new visible scarring as the entry port for the instruments is the mouth, the nose, the anus, the vagina or the urethra for NOTES, or the umbilicus (that can be seen as a cicatrized natural orifice) for SPA. NOTES and SPA are intended to further reduce postoperative complications compared to traditional laparoscopic MIS. This is not yet in common clinical practice,

even if hundreds of operations have been performed in preclinic tests on humans worldwide (cholecystectomies, appendectomies, tubal ligations, hysterectomies, gastric sutures, colic sutures, etc.) [MAR 07a, SWA 07].

For NOTES, the technique relies on the use of cable-driven flexible endoscopes with flexible instruments passing through service channels, with which the surgeon can reach and operate the targeted internal organ. Dedicated prototypes have been developed, with additional DoFs to provide enough mobility to the instruments as the examples in Figure 1.9 depict. However, the manipulation is difficult and non-intuitive for a surgeon alone due to the high number of DoFs and the flexibility. One solution is to require the assistance of a second surgeon, another is to robotize the flexible endoscope such that it can be operated by one surgeon from a master robot. As underlined in [TIW 10], robotics may provide better visualization, precision and maneuverability in large cavities, fine motor control of endoscope distal tip and enhanced surgical dexterity.

Figure 1.9. *Manual flexible endoscopes for NOTES: a) tip of the R-Scope from Olympus Optical; b) Cobra from USGI Medical: the flexible sheath is rigidly lockable at any time in a desired configuration; c) close-up of the tip of Cobra*

An example of a robotized endoscope for gastrointestinal (GI) procedures is shown in Figure 1.10(a). It shows the 3D model of a two-arm manipulator attached to a flexible endoscope [LOW 06], each arm having five DoFs, not

accounting for the opening/closing of the end effector. Tendon-sheath actuation is used. The arms are teleoperated from a master system. The size of the whole manipulator is approximately 25 mm in diameter. Compared with conventional colonoscopes with working channels through which a tool can be inserted, for instance, to cut a polyp, such manipulator may serve to perform more dexterous actions such as suturing.

Another concept was implemented in the prototype of the Anubis project [BAR 12] as shown in Figure 1.10(b). It consists of a flexible endoscope (from Karl Storz Endoskope GmbH) and two flexible hollow arms. Each of these three parts is made up of a long flexible passive shaft and an articulated distal tip. The hollow arms are fixed on the circumference of the main endoscope at the end part of its bending tip. This is done due to a special end cap that deflects the arms from the main direction of the endoscope to provide triangulation between the arms and the endoscope. The distal tip of each arm provides two DoFs to which the translation and rotation of the instrument inside the arm should be added.

Figure 1.10. *Robotized endoscope for NOTES: a) a two-arm manipulator attached to a flexible endoscope from Nanyang University, Singapore [LOW 06]; b) head of the prototype of Anubis project [BAR 12]*