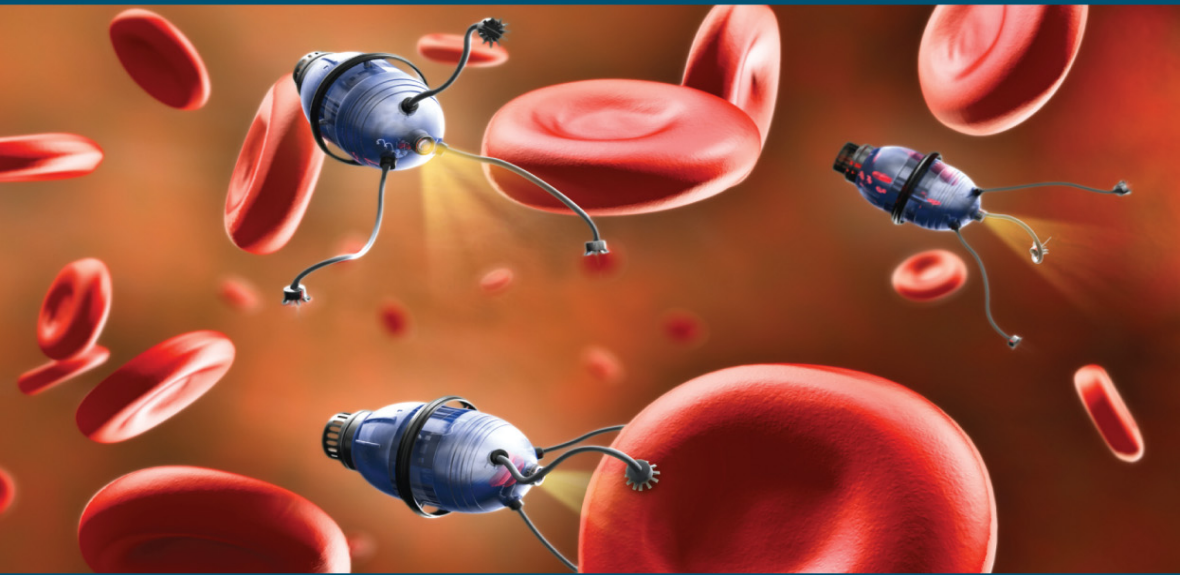


ROBOTICS SERIES



Intracorporeal Robotics

From Milliscale to Nanoscale

Michaël Gauthier

Nicolas Andreff and Etienne Dombre

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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 Robotics¹, 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.

1 [http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshop Report.htm](http://www.nsf.gov/eng/roboticsorg/IARPMedicalRoboticsWorkshop%20Report.htm).

Fields of application	Potential benefits to the surgeon	Potential benefits to the patient
–Orthopedic surgery	<ul style="list-style-type: none"> – ↗ Precision – Possibility of carrying out complex cutting, drilling, milling – Integration of multimodal preoperative and intraoperative information (vision, force) – ↗ safety (virtual fixture) 	<ul style="list-style-type: none"> – Less revision surgery – Expected longer lifetime of prostheses
– Minimally invasive endoscopic surgery	<ul style="list-style-type: none"> – 3rd hand – Greater comfort – Elimination of the fulcrum effect – Additional internal mobilities – Compensation of physiological movements 	<ul style="list-style-type: none"> – Toward an increasingly less invasive surgery and without visible scars
<ul style="list-style-type: none"> –Neurosurgery –Interventional radiology –Radiotherapy 	<ul style="list-style-type: none"> – ↗ Precision – ↗ Safety (avoidance of vital structures) – Compensation of physiological movements – ↘ Exposure to radiations – Precise spatial tracking of the dosimetric planning 	<ul style="list-style-type: none"> – ↘ Invasiveness – Early treatment of increasingly smaller tumors – ↘ Exposure to radiations of healthy tissues
–Microsurgery	<ul style="list-style-type: none"> – Downscaling of the forces and displacements – Surgeon’s tremor filtering 	<ul style="list-style-type: none"> – Development of innovative procedures beyond the accuracy limits of the surgeon

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

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 Society² has launched a Technical Committee on Roboethics³ 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 Robots⁴ was held at ICRA 2013. It was organized by the partners of the FP7 project RoboLaw⁵. One can also refer to the pioneering initiative of G. Veruggio⁶ in the framework of the European Robotics Research Network (EURON) and the work of R.C. Arkin⁷ 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

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/>.

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.

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

2 Intracorporeal Robotics

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.

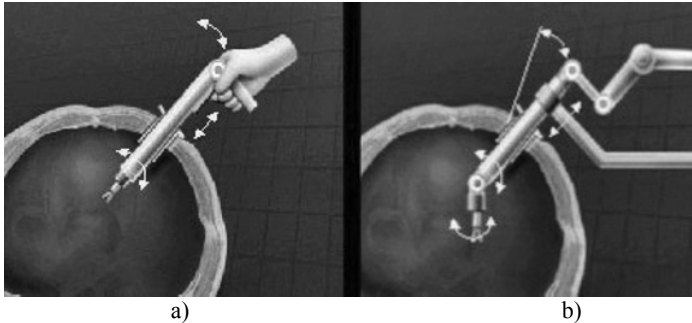


Figure 1.1. *Partially intracorporeal DoFs: a) comanipulated instrument; b) teleoperated instrument [SAL 04]*

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 Motion¹) and Da Vinci (Intuitive Surgical²), 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.

¹ Merged with Intuitive Surgical since 2003.

² <http://www.intuitivesurgical.com/>.

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.

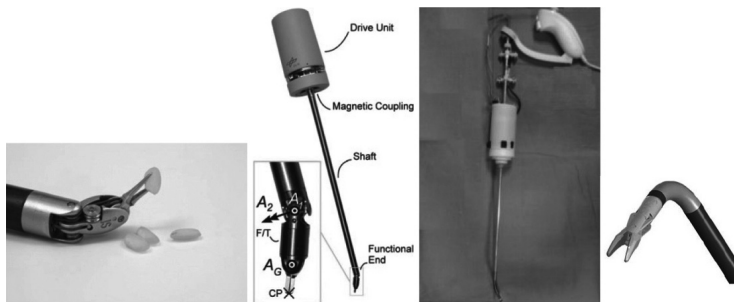


Figure 1.2. From left to right: close-up of the Da Vinci Endowrist tip manipulating rice grains; DLR MICA instrument of the MIRO platform for endoscopic surgery and close-up of the two-DoF wrist mounted with a force/torque (FT) sensor [HAG 10]; the EndoControl³ handheld laparoscopic instrument JAI MY [ZAH 10]; close-up of the two-DoF bending and rotary wrist of JAI MY

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 ablation, 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,

³ <http://www.endocontrol-medical.com/>.