Medical Robotics
Chapter I. Introduction

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   B. Orthopedic surgery;
   C. Head and neck surgery (neurosurgery, maxillofacial surgery, dental surgery);
   D. Interventional radiology and percutaneous procedures;
   E. Assistance to ultrasound examination;
   F. Radiotherapy.
1. GENERAL CONSIDERATIONS
Why using robots for medical interventions?

• Potential advantages of robotic manipulation over human manipulation:
  – speed; precision; repeatability;
  – No tiredness.
  – Automatic trajectory tracking;
  – Easy integration of position and/or force constraints;
  – Real time fusion of multimodal exteroceptive data
  – Data recording.
However

- Humans are still better than robots in many domains, e.g.:
  - Capacity of analyzing a complex situation and producing a decision;
  - Ability to adapt, even to improvise;
  - Ability to long life learning;
  - Ability to integrate disparate and multimodal data sources with complex contents

⇒ keep the human user in the loop
Typology

“Autonomous” robots

- Limited autonomy: the loop with the surgeon is loose (timewise)
- The surgeon gives high level instructions
- The robot translates into simple tasks
- Condition: the gesture can be described as a simple task for a robot...

Collaborative robots

- Robotized instruments
- The surgeon is in the loop in real-time and controls the robot movements
- Control sharing
- Telemanipulation (the surgeon is at a distance) vs comanipulation (surgeon + robot co-localized).
Two types of collaborative robots

Telemanipulation

Comanipulation

Parallel comanipulation
Serial comanipulation
Orthotic comanipulation
What is specific to medical robotics?

• Environmental constraints:
  – Safety nearby patients and personnel
  – Sterility
  – Operating Room

• Difficulty for validation:
  – Technical and economical feasibility
  – Proof of medical service.
  – Human factors.

• Regulatory issues : CE marking and/or FDA approval.

Safety for patients and medical personnel

• Zero « accident » accepted. At a minimum :
  – A doctor in the loop;
  – Precise protocols, well documented, with adequate training for medical personnel;
  – Human machine interfaces: intuitiveness, ergonomics, without ambiguities;
  – Automatic initialization procedures;
  – Clear and fast procedures for conversion to manual intervention;
  – Intrinsically safe robotics architectures, e.g.:
    • Mechanical fuses, mechanical balancing
    • Electrical fuses, redundant sensors, electronical watchdogs
    • Limitations for workspace, velocity, forces
    • Safe behavior in case of power supply failure
  – Procedures for individual testing software and hardware components;
  – Procedures for step-by-step validation of all the medical treatment steps.
Sterility

All parts in contact with the patient or surgeon should be:

1. Sterilizable, according to different processes, mainly:
   - Autoclave: steam sterilization - 134 ° / 18 minutes.
   - STERRAD: The Sterrad® process (Johnson & Johnson Division ASP®) uses hydrogen peroxide as a sterilizing agent during a plasma phase cycle. The cycle proceeds at low temperature (50 ° C); It makes it possible to sterilize certain thermosensitive medical devices, subject to the limits of use of this method.

2. Disposable in sterile packaging (preop).

3. In sterile packaging (perop).
Sterilizable robot vs robot with sterile packaging.

Endoscope Holder ViKY, TIMC, Endocontrol

da Vinci Robot, Intuitive Surgical
OR technical constraints

• The overall footprint shall be reduced;
• The robot workspace should be "perceivable" (eg using easy-to-read architecture);
• Moving and installing the robotic system and controller should be easy, preferably by one person; The robotic system shall easily be brought in and out of the operating room;
• Precise procedures for storing and maintaining accessories should be given;
• Preventive maintenance shall be organized;
• Effective management of failures is to be provided;
• Electrical and magnetic compatibility with other equipment is required by regulations (regulatory testing);
• Additional professional staff should be avoided, etc.
Success factors

• Necessary success steps:
  – Technical
  – Medical
  – Clinical
  – Commercial

• The engineer / researcher should ask, at a minimum, whether:
  – The project is based on a quality medical expertise
  – The prototype has a reasonable chance of becoming a certifiable system;
  – The robotic system will objectively allow the improvement of the gesture practiced by the doctor;
  – This improvement is potentially significant for the patient or for the medical staff.
  – Not to mention human factors.

⇒ It must be said: very few successes to date!
Historical perspective: 1985-2000

• Phase 1: Mid-1980s: First crazy people use industrial robots to precisely position surgical instruments, particularly in brain surgery, by coupling with a navigation system. In the 1990s, development of this concept in orthopedic surgery (hip, knee, spine).

• Phase 2: Mid-1990s, minimally invasive surgery (developed in manual practice in the 1980s). Teleoperated systems designed to increase the dexterity and comfort of the surgeon.
From the beginning of 21st century

• Diversification:
  – Compact & dedicated devices
  – Robotics "inside the patient“:
    • N.O.T.E.S (natural orifice transluminal endoscopic surgery)
    • Active catheterization, endoscopy and dexterous instrumentation,
  – Real-time image guidance
  – Compensation of physiological movements:
    • Respiratory
    • Cardiac

• New aspects taken into account:
  – Advent of the human-robot interaction as a central subject in robotics (not just in surgery)
  – Human factors
2. MAIN APPLICATIONS
Main applications

Hereafter are some example existing applications sorted by clinical domains:

A. Minimally invasive thoracic and abdominal surgery;
B. Orthopedic surgery;
C. Head and neck surgery;
D. Interventional radiology and percutaneous procedures;
E. Vascular and cardiac surgery;
F. Radiotherapy and diagnostic radiology
G. Assistance to ultrasound examination.

This list is not exhaustive. Rather, examples were chosen to illustrate the diversity of the domain and the main challenges raised by the current vision of surgery and surgical robotics.
A. Minimally invasive surgery

- A (French?) proverb in the early 20th century: “great incision, great surgeon” (remember that this was *without anesthesia*).
- In fact, it has been progressively understood that incisions are causing a large number of postoperative complications.
- Minimally invasive surgery (MIS) = limiting the size (and number) of incisions + limiting the unnecessary trauma.
- Historically, this has started with endoscopy (“looking inside”) for diagnostic purposes.
- In general, MIS consists in insertion of elongated optical device (to see) and instruments (to act).
- Much less trauma (the most promising way towards day surgery according to WHO), which implies:
  - High benefit for the patient.
  - High economical benefit.
  
  *This combination is rather rare* and has favored the development of MIS for the past 30 years.
- A main drawback has limited its development: MIS is much more difficult for the surgeon than conventional (large incision) surgery ➔ robotics has a role to play.
Laparoscopic surgery

- The most popular implementation of MIS
- Applies to “general surgery”, abdominal, thoracic, gynecological, urological surgery, etc. (everything in the abdomen and thorax)
- Abdomen inflated
- Endoscope (diam. 10mm) inserted through the belly button.
- 1 to 4 instruments (diam. 5 to 10 mm) inserted at locations selected from anatomical and ergonomics constraints.
Laparoscopic surgery

• Procedure is longer (danger for the patient due to longer anesthesia) and more complex for the surgeon
• Often requires two surgeons (1 “operating surgeon” + 1 assistant)
• Tiring and dangerous (musculoskeletal disorders)

➤ Practiced mostly for simple and short procedures (e.g. cholecystectomy, appendectomy, ...).
Robots

- Endoscope holders: replacing the assistant who position and holds the endoscope

AESOP (voice control, 4 active DoFs, 2 passive)

VIKY (Voice + pedal control, 3 active DoFs)
Vicky: autonomous / teleoperated
Robots

- Zeus: the 1st teleoperated MIS (a system made with 3 AESOPs)
- Two instruments + one endoscope manipulated by 3 robotic arms while the surgeon is installed comfortably and distantly

Robots

- Da Vinci by Intuitive Surgical: the most successful surgical robot, by far (more than 3 Million interventions)
- Console with 3D endoscopy and distal dexterity
Robots

- Robotized laparoscopic instruments
MIS is not limited to laparoscopic surgery

• It is also developed in all the other domains of surgery (orthopedic, neuro, etc.)

• For general surgery, a tendency is to try limiting even more the invasiveness:
  – Single port surgery: only one incision is made, all the instruments go through.
  – N.O.T.E.S. (Natural Orifice Transluminal Endoscopic Surgery) also called no scar surgery.
Single Port Surgery
Titan Medical’s SPORT

USER TOUCH POINTS
WORKSTATION
- HD 3D Display
- Secondary Touch Screen
- Master Controllers
- Hand Controllers
- Surgeon Interface

USER TOUCH POINTS
PATIENT CART
- Adjustable Muni
- Cart Push Handle
- Caster Lock Pedal (Secures the cart when in use)

INSTRUMENTS
REPLACEABLE END EFFECTORS
- S-Works Section
  - Translational movement
- Distal Section
  - 2-axis multi-articulated movement
- Tip Section
  - Rotation + opening/closing movement
- Scissors (monopolar compatible)
- Hook (monopolar compatible)
- Needle Driver
- Laparoscopic Grasper

Dissector (monopolar compatible)
Titan surgical’s SPORT
N.O.T.E.S.
Stras robot, ICUBE lab
B. Orthopedic surgery

- This surgery concerns the skeleton: limbs, basin, rachis, joints.
- It was amongst the early adopters for robotics.
- It has common characteristics with conventional robotics:
  - Process= machining(cutting, milling, drilling, etc.).
  - Bones are often immobilized.
  - Bones can be considered as rigid bodies (not deformable).
A true pioneer: Robodoc

- Planning + registration+ milling the bode at an appropriate shape to receive a prosthesis.
- Gain over human: precision, repeatability, tracability,
- Very difficult to prove the medical benefit (outcomes after years)
Comanipulation for orthopedic surgery

A pioneer: ACROBOT

SURGICOBOT: able of adapting in real time to bone movements (rachis)

MAKOPLASTY: allows for minimally invasive access
A miniature orthopedic surgery robot

- It is bone mounted and used to position a cutting guide
C. Head and neck surgery

• Head and neck surgery includes: stereotactic or conventional neurosurgery, ophthalmic surgery, otorhinolaryngologic surgery (ENT), maxillofacial surgery, dental surgery.

• This surgery is characterized by a very high precision requirement, either in the positioning of the tools relative to the anatomy of the patient, or in the manipulation of bone fragments (cutting, repositioning).

• Frequent use of microsurgery (surgery under a microscope) or endoscopy.
C.1 Neurosurgery

- Traditionally, neurosurgery uses minimally invasive access and «navigation».
- Neurosurgeons invented the stereotaxic frame (early 20th century) for:
  1. Providing an external reference frame to localize an intracerebral anatomical structure;
  2. Immobilizing the patient's skull when performing minimally invasive procedures requiring millimetric accuracy;
  3. Provide a support for the arm.

⇒ A pioneer domain for quantitatively using imagery for localization.
Robotics easily integrates within this framework

- NEUROMATE (1995) is a robot used to position a needle guide (semi-active comanipulation)
- ROSA can be viewed as an evolution from Neuromate. Used e.g. in electrode placement for epilepsy treatment. No more stereotaxic frame.
C.2 Eye surgery: the example of retina cannulation

- Vibrations
- Rotation
- 10 µm
- ±167 µm
- 3 min - 45 min
Application of the concept of comanipulation to retina cannulation

incision point (RCM)
Application of the concept of comanipulation to retina cannulation
C.3 ENT (Ear-Nose-Throat)

Robotol: colocalized telemanipulator for ear surgery
TORS : Trans Oral Robotic Surgery
Laser PhonoMicroSurgery
D. Interventional radiology

• Today radiologists perform interventional gestures using needles, probes, catheters or the like, guided peroperatively by one or more imaging modalities.

• 2 types of interventions are realized:
  – Vascular procedures: introduction of a catheter into a vein or artery, angioplasty, stent placement, prosthesis placement, embolization;
  – Percutaneous gestures (introduction of a needle to reach a target): biopsies, infiltrations, tumoral treatment, brachytherapy.

• Imaging modalities include:
  – RX (C-arm - CT Scan);
  – MRI;
  – Ultrasound.
What robots can bring to interventional radiology

• Precise positioning of the needle tip thanks to the coupling of image and robotic manipulation;
• Manipulation of needles inside an MRI or CT-Scan machine from a distant site (telemanipulation), knowing that both are uncomfortable while CT-Scan is further dangerously radioactive.
• Manipulating flexible catheters and needles with distal dexterity.
• Manipulating imaging devices in the OR (precise and optimal positioning).
An early example of needle manipulation under CT Scan
A comanipulated needle holder concept from DEMCON
LRP (TIMC Grenoble), an MRI compatible device

Fully plastic, patient mounted
CTBOT @ LSIIT Strasbourg (now known as ICUBE)

- Designed to guide a needle in the CT Scan
- Includes fiducials in situ for registration (as we will see in detail in chapter 1)
A catheter manipulator: SENSEI, Hansen Medical
Positioning an X-Ray imager in the OR (fluoroscopy)
E. Assistance to ultrasound imaging

• Ultrasound imaging:
  – Requires manipulating a probe in contact with the patient (with a controlled force)
  – Provides a real time visual feedback in true 2D (≠ projection of 3D elements on a plane).
  – Involves exploration and tracking of anatomical structures (⇒ mental 3D reconstruction)
  – Is highly dependent on the operator’s expertise
Pioneer examples

On the left: Hippocrates, comanipulated, used to build 3D volumes thanks to the combination of 2D imaging + precisely robot-controlled movements

On the right: a pioneer Teleoperated ultrasound robot.
Patient-mounted teleoperated ultrasound robots

Figure 1.23. *A gauche : TER en action ; à droite : zoom sur le porte-sonde*
Comanipulation for assistance to US-guided prostate biopsy
Apollo: First patient
F: radiotherapy

• Principle: burning a tumor with a radioactive beam (X-ray, protons, etc.)

• Main problems:
  – Targeting the right place (not visible but with another imager)
  – Limiting the alteration of healthy tissues
  – Following moving tumors (e.g. lung)
Accuray’s Cyberknife

**Figure 1.25.** CyberKnife® (à droite) et le positionneur de patient Robocouch® (à gauche : un porteur SCARA + 1 poignet sphérique à 3 ddl) d’Accuray
Accuray’s Cyberknife
Patient positioning for protontherapy

(to be studied in more details in Chap. 1)
Conclusive remarks

• A domain in constant expansion

Total Image-Guided and Robot-assisted Surgery Market: Western Europe, 2011

Market Overview

<table>
<thead>
<tr>
<th>Market Stage</th>
<th>Market Revenue</th>
<th>Market Size for Last Year of Study Period</th>
<th>Base Year Market Growth Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Growth</td>
<td>$888.0 M</td>
<td>$1,697.5 M</td>
<td>8.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compound Annual Growth Rate</th>
<th>Customer Price Sensitivity</th>
<th>Degree of Technical Change</th>
<th>Estimated Market Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.7%</td>
<td>7</td>
<td>8</td>
<td>More than 70%</td>
</tr>
<tr>
<td>(CAGR, 2011–2018)</td>
<td>(scale:1 [Low] to 10 [High])</td>
<td>(scale:1 [Low] to 10 [High])</td>
<td>(% of market share held by top 3 companies)</td>
</tr>
</tbody>
</table>
Conclusive remarks

• Example: da Vinci numbers
Conclusive remarks

• Extremely variable robots shapes & functions, many more applications / developments than those cited in these slides

• Common features:
  – Very high demand for personalized medicine and quality based medicine
  – Technical challenges due to the adaptation to the environment / reliability / sterilization
  – Very difficult path to the market / clinical success (even more difficult than the technical challenges)