Kinematics, position and force control issue in minimally invasive surgery

G. Morel* and P. Poignet**

* LRP, Paris, France

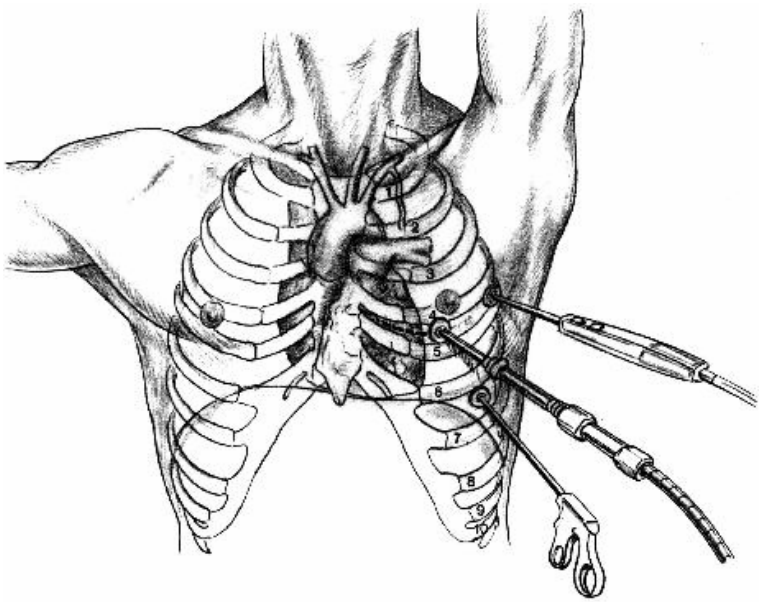
** LIRMM, Montpellier, France

morel@robot.jussieu.fr

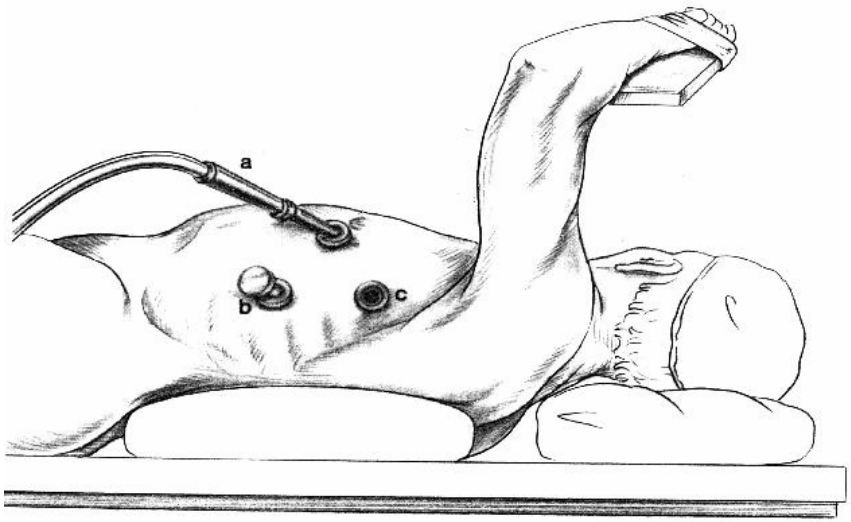
poignet@lirmm.fr

Introduction

Minimally invasive surgery (MIS)



- Long instruments
- Small incisions
- Endoscope for visual feedback



Drawbacks or difficulties in MIS

- Penetration point ➲ accessibility, loss of degree of freedom or mobility, reduced orientation capabilities and limited amplitude of motions

- Hand-eye coordination (reverse hand motion, scaling of motion,…)

- Loss of natural haptic feedback ➲ increased difficulty for knotes, force sensing, lead traction,…

- Reduced point of view

Solution: Robotized Minimally Invasive Surgery

The surgeon manipulates instruments through a master device. The instruments are moved by robotized manipulator

Open problems

- Kinematics (guaranteeing trocar constraint, redundancy,…)
- Distal mobilities for increasing manipulability or dexterity inside patient
- Technology (mechanism, actuator, sensor, space occupancy, …)
- Control architecture (accuracy, force feedback, correct hand–eye coordination, scaling position and/or force,…)
- Gesture assistance functions (physiological motion compensation, automatic camera guidance,…)
- Safety

Introduction

General objective: Design **kinematics** and synthesize a **control architecture** providing **force feedback** and **augmented vision** of the operating site to the surgeon by means of a **teleoperated** master slave system with **high dexterity**

- Control the interactions between instruments and organs
- Full dexterity

- Provide surgeon force feedback
- Augmented sight of the operating area

Contents

- Kinematics and motion control
  - Carrier
    - **Constrained kinematics** / spherical wrist
    - Position control (geometric control approaches, dynamic decoupling control,…)
    - Force control
  - High dexterity instrument
- Interaction control
- Teleoperated systems

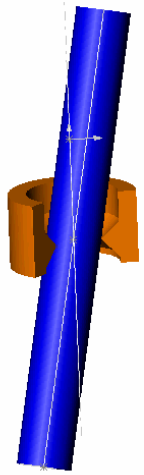
Instrument carrier

- Arms with kinematics constraint
  - The idea is to create a mechanical structure able to give the tool one SPECIFIC type of motion
  - Mostly applied to mini-invasive surgery

- M.I.S. ➔ a tool (shape ⇔ cylinder) passes through a trocar (shape ⇔ annulus)

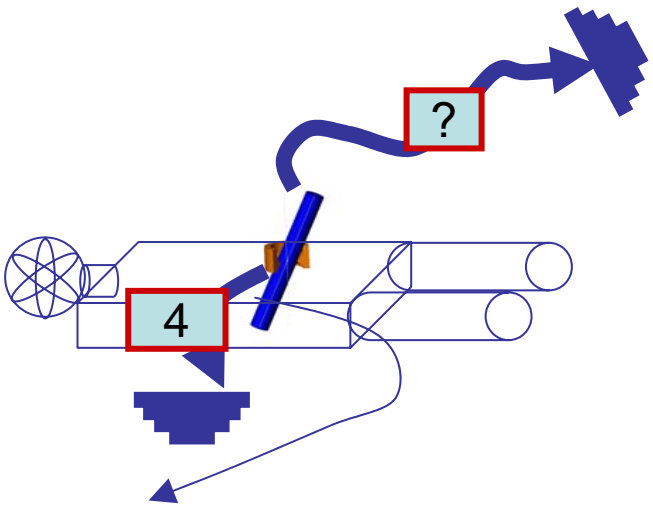
- The tool axis always passes in one “fixed” point

- Two constraints (translation is constrained in two directions)



How many dof for respecting the constraints?

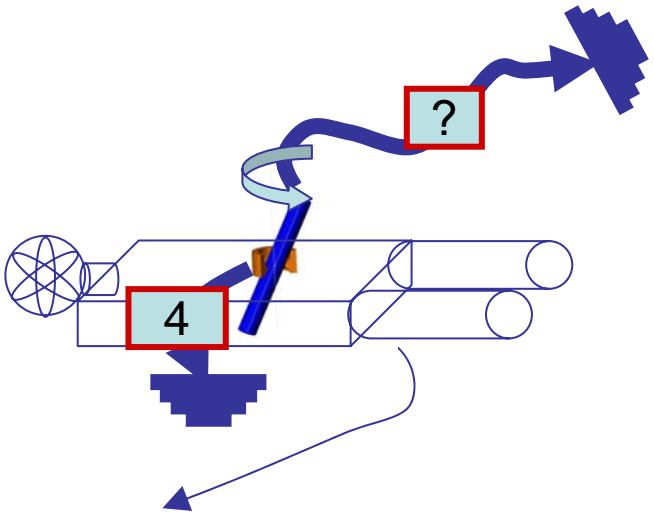
- Gruebler formula: Mobility = (Total dof) – (6 x Nb of loops)



Mobility ➔ Tx, Ty, Tz ➔ 3

3 = (4 + ?) – (6 x 1)

➔ ? = 5



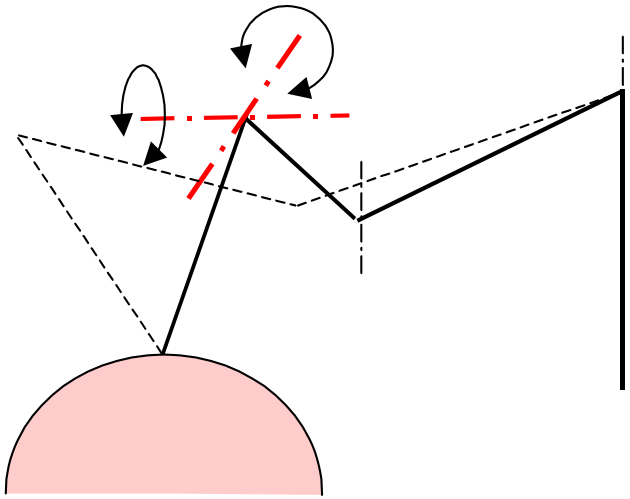
Mobility ➔ Tx, Ty, Tz, Rz ➔ 4

4 = (4 + ?) – (6 x 1)

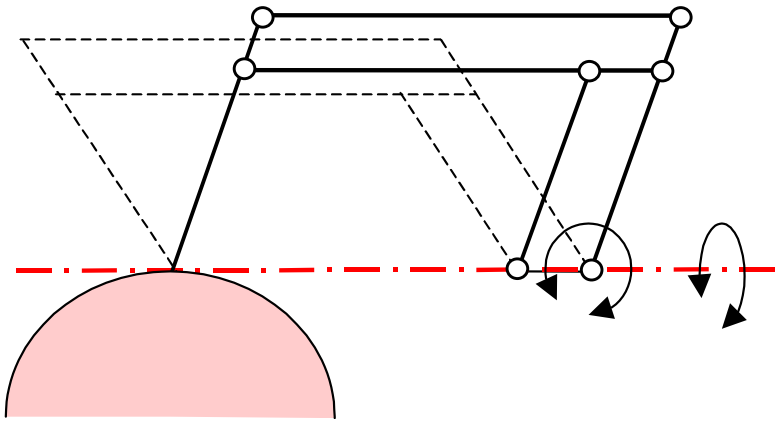
➔ ? = 6

Kinematics architecture

- Well known slave kinematics to mechanically create a fixed point that coincides with the penetration point



Passive universal joint (Zeus)



Remote center device (da Vinci, Artemis…)

Option 1: passive joints

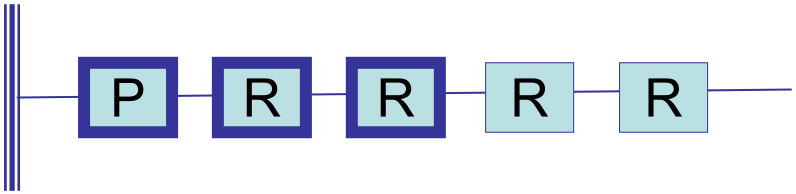
- Mobility ➔ Tx, Ty, Tz ➔ 3
- 3 = (4 + 5) – (6 x 1)

5 joints

-

3 motors

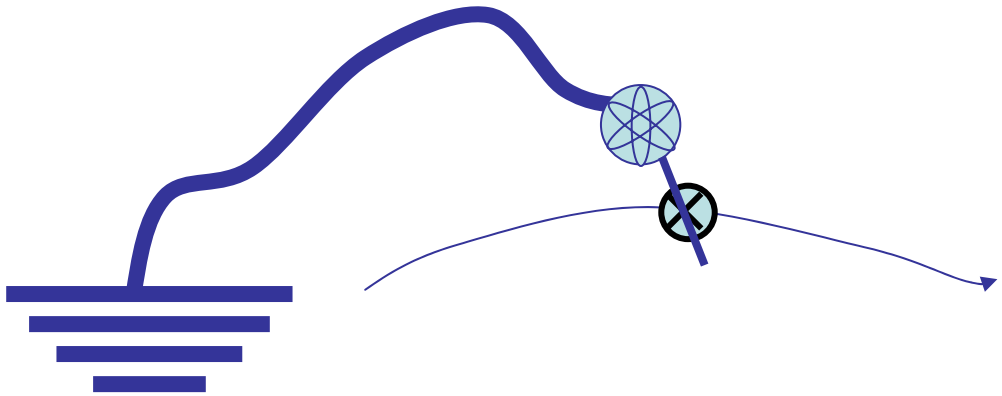
2 passive joints



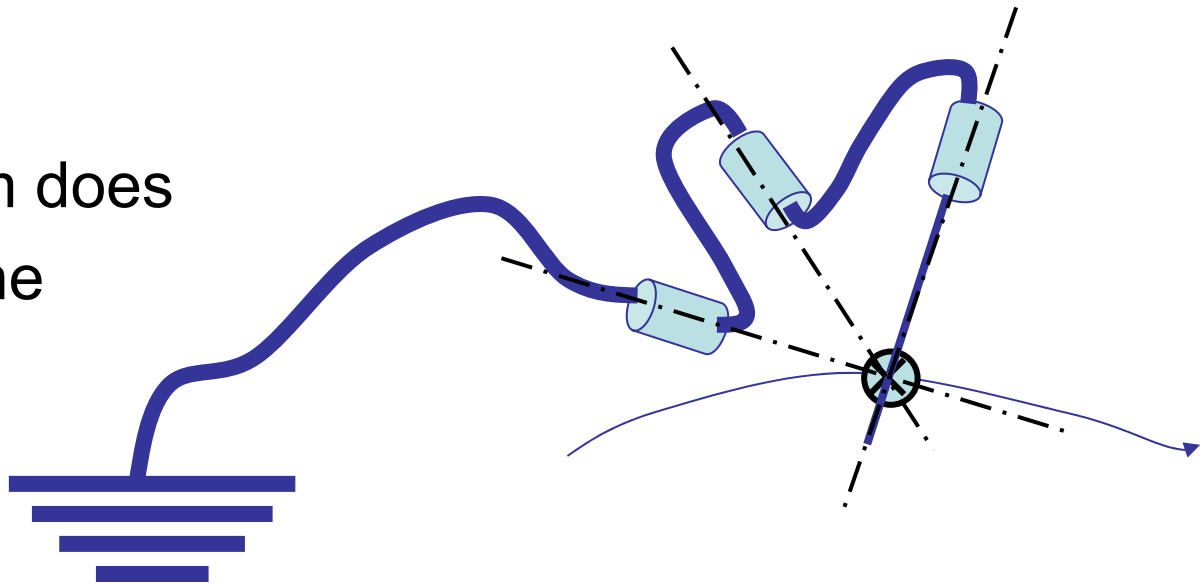
Zeus

Option 2: Remote Center of Motion

- A classical spherical wrist does not rotate at the “right” point



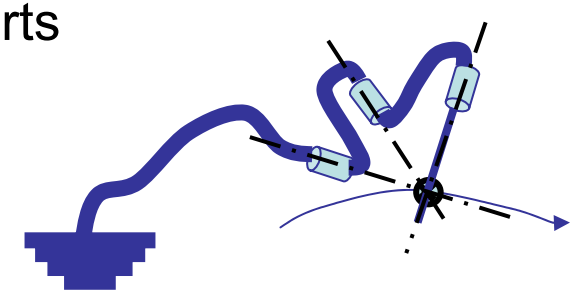
- A RCM system does and thus “cancel” the constraint



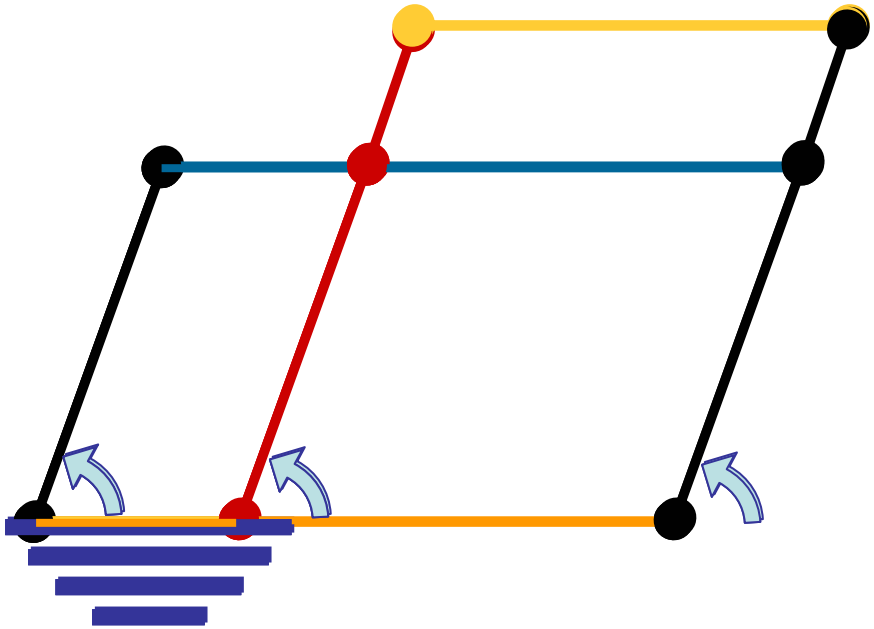
RCM or “The Magical Parallelogram”

- RCM with spherical links requires complex parts but can be more compact

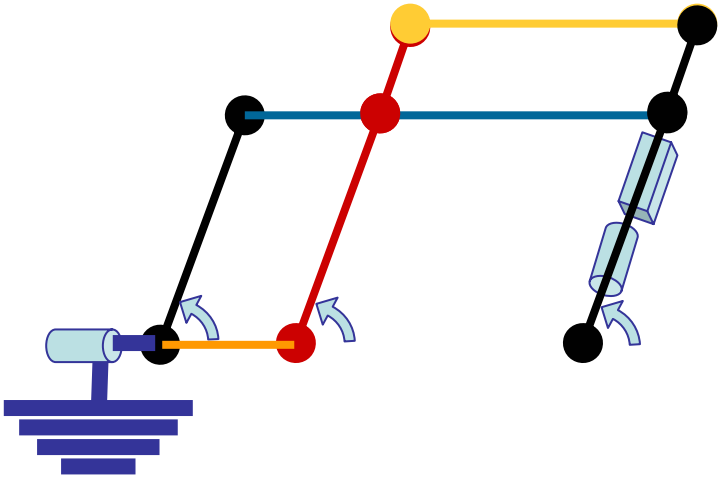
  (See examples later)

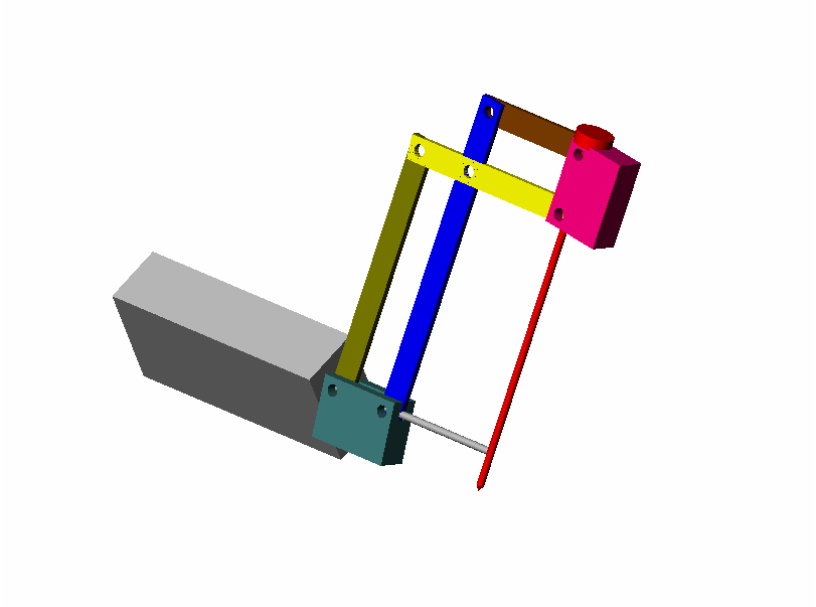


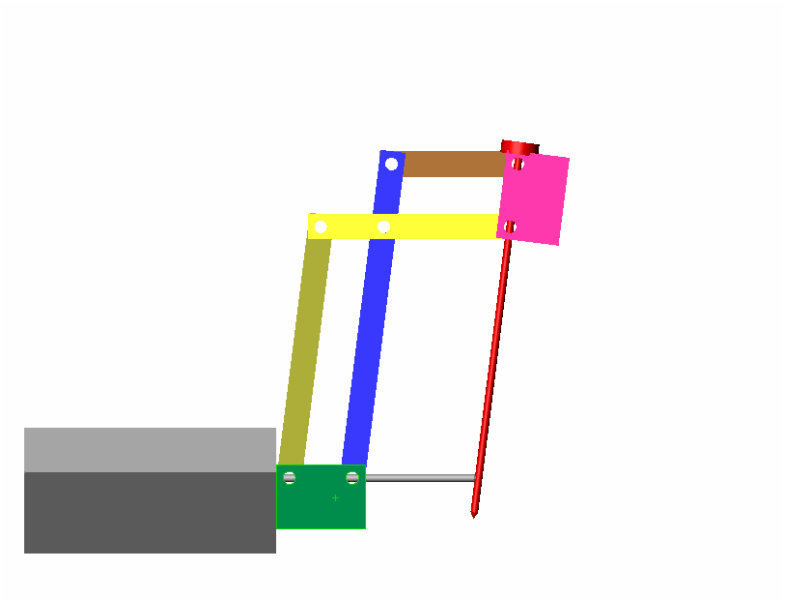
- … while a basic parallelogram may do the job as well



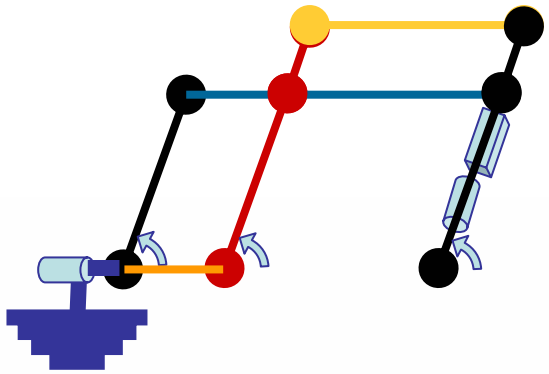
RCM in motion



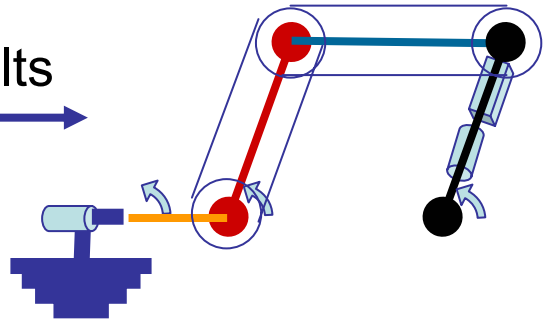


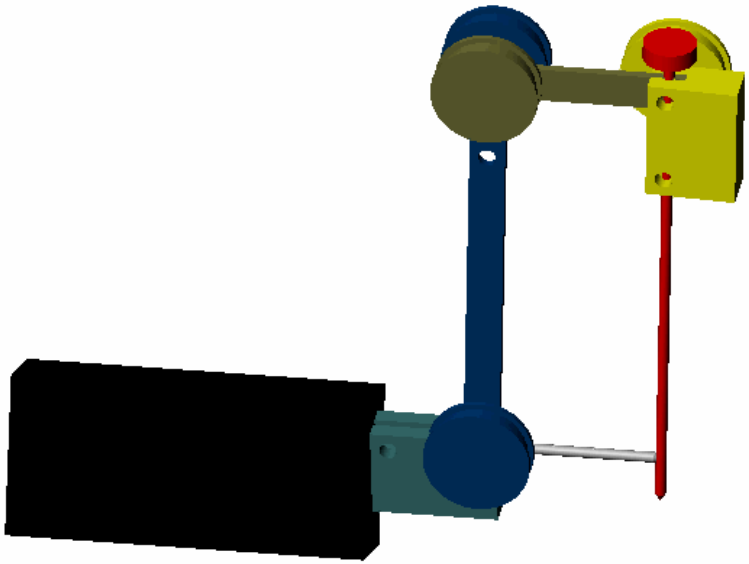


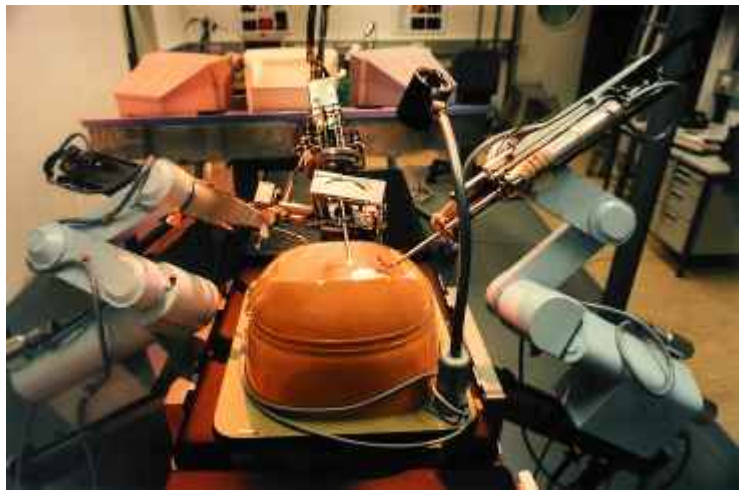
RCM: other solutions…



From solid links to timing belts







ARTEMIS - FZK

Summary of solutions with kinematics constraint

- Option 1 (passive joints)
  - Few motors
  - The trocar “forces” the passive joint to adapt “mechanically”
  - No accurate positioning is needed
  - Safety at the expense of motion accuracy and stiffness
- Option 2 (active RCM)
  - Few joints and motors
  - The trocar has no influence on the arm motion
  - BUT, the arm MUST be precisely located (positioning device + procedure)

Spherical wrist

Contents

- Kinematics and motion control
  - Carrier
    - Constrained kinematics / **spherical wrist**
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Spherical wrist and portable solutions…

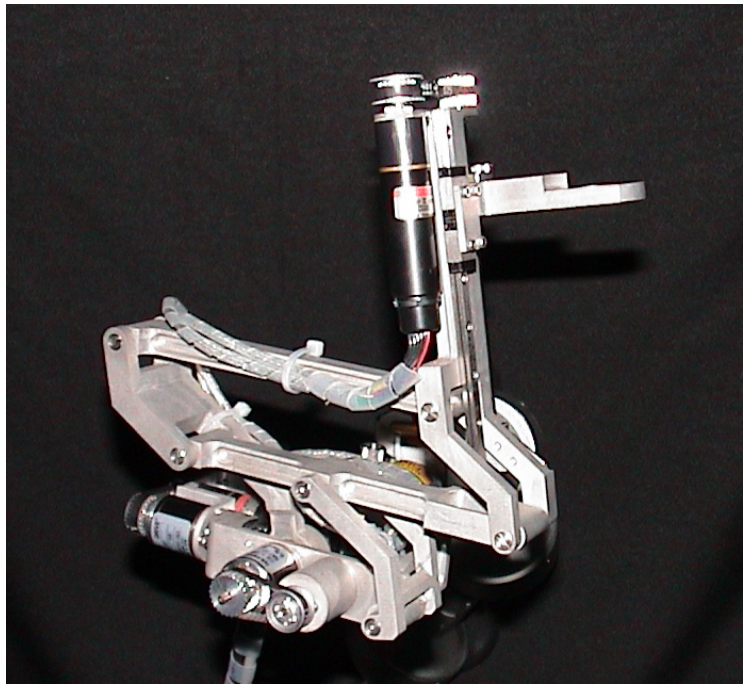
Small occupancy robotics mechanisms for endoscopic surgery [Nakamura 2002]

Problem: « the occupation of the space in operating room ! It sometimes prohibits surgeons from accessing patients in an emergency ☹ surgical robot systems should be small. »

Active trocar:

2-dof rotation
1-dof translation

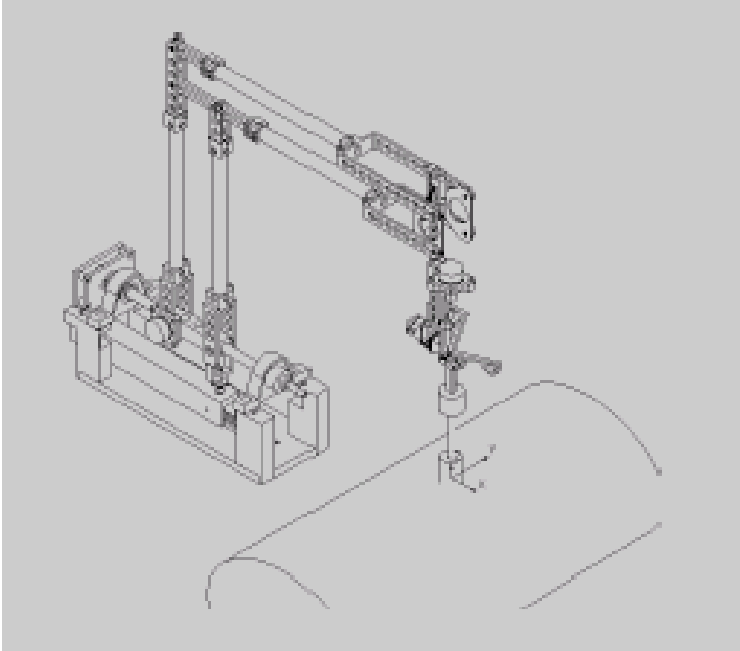
Weight: 1kg including the drive part



Spherical wrist and portable solutions…

- Spherical optimized mechanism [Hannaford 04] wrt workspace requirements for MIS and practical joint limits

Blue DRAGON: system for measuring the position and orientation of two endoscopic tools along with the forces and torques applied to the tools in a minimally invasive environment [Hannaford 02].



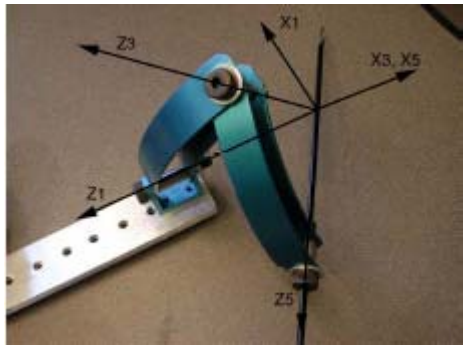
Spherical optimized mechanism [Hannaford 04]

Generic surgical tasks: tissue handling/examination, tissue dissection and suturing.

Analysis performed on an animal model in-vivo by 30 surgeons: 95% of the time the surgical tools positions encompass a 60º cone.

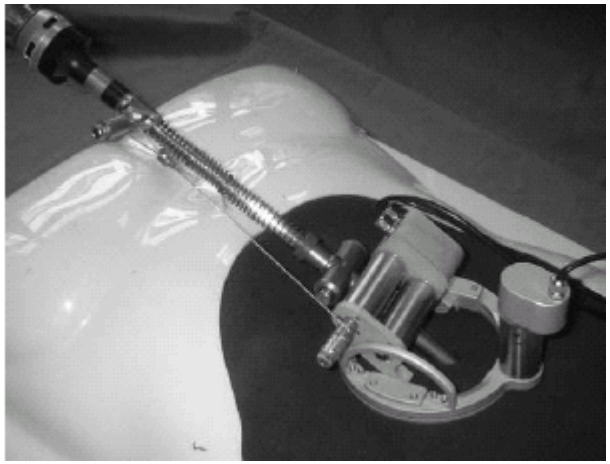
Reachable workspace of an endoscopic tool performed on a human model: to reach the full extent of the abdomen the tool needed to be moved 90º in the lateral/medial direction (left to right) and 60º in the superior/inferior (foot to head) direction.

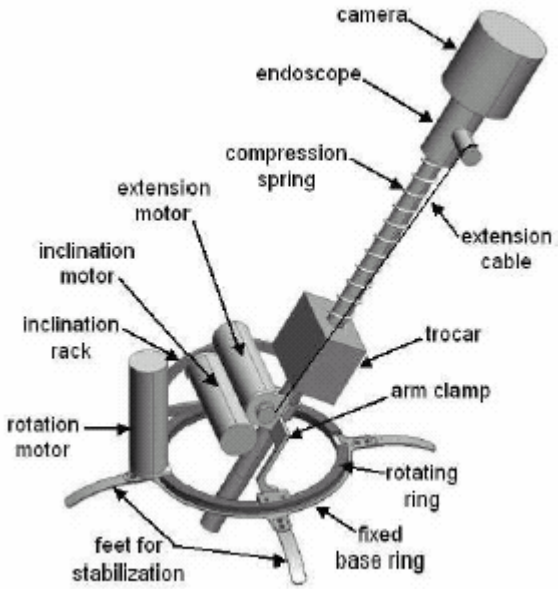
- Design space optimization wrt mechanism isotropy



Spherical wrist and portable solutions…

- LER Light Endoscopic Robot [Berkelman 03] [TIMC, Grenoble, France]





Mass:

LER 625 g

Endoscope and Camera 300-500 g typical

Backdriveability:

Torque 0.45 N.m

Backdrive force on fully extended endosc. 1.5 N

LER [TIMC, Grenoble, France]

Dimensions: height 75 mm, diameter 110 mm

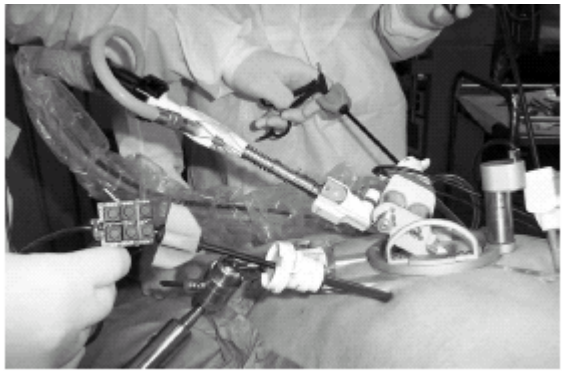
Motion range: azimuth rotation 360° continuous, inclination to 80° from vertical, extension 160 mm

Max. speed: azimuth rot. 20 deg.s^{-1}, inclination 20 deg.s^{-1}, extension 25 mm.s^{-1}

Max. torque limit: 6 N.m

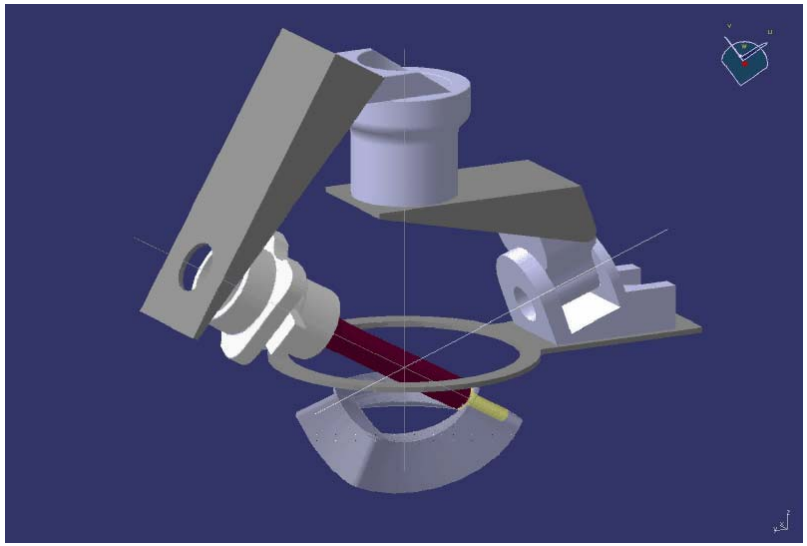
Max. force on fully extended endoscope: 20 N

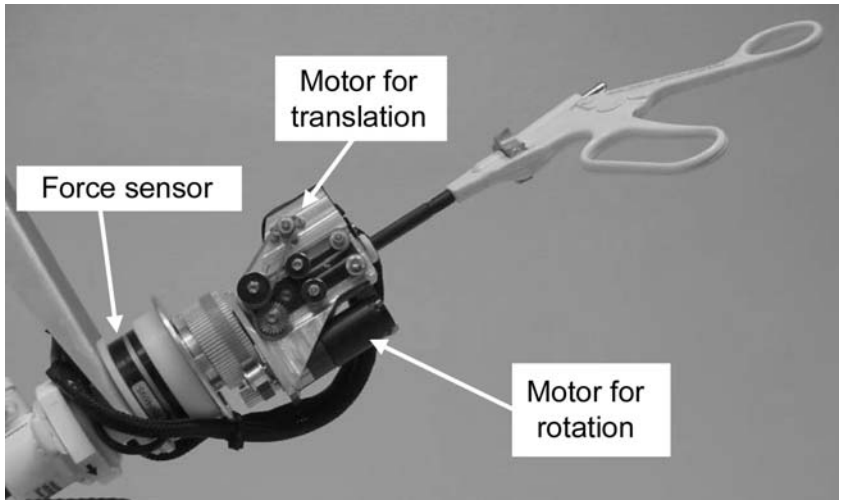
Voice control



Spherical wrist and portable solutions…

- MC^{2}E [LRP, Paris, France]





- **Lower part:**
  - spherical 2-dof mechanism (Θ_1 and Θ_2)
  - intersecting axes realize fulcrum point
- **Upper part:** mounted on trocar (Θ_3 and d_4)
- **Currently 4-dof at distal end**

MC²E [LRP, Paris, France]

The bone-mounted miniature MARS robot [Shoham 2003]

• precise position and orientation of long, handheld surgical instruments, such as a drill or a needle, with respect to a surgical target

• small work volume enclosing a sphere whose radius is several centimeters

• lightweight and compact structure

• lockable structure at given configurations to provide rigid guidance

• capable of withstanding lateral forces resulting from instrument guidance of up to 10 N

• repeatedly sterilizable in its entirety or easily covered with a sterile sleeve

• quick and easy installation and removal from the bone.

- Option 3 (spherical wrist)
  - The wrist may require complex parts
  - But it can be easily located on the trocar
  - However it is still rather cumbersome on the patient if the surgeon has to locate 3 of them

Position control + versatile carrier

Contents

- Kinematics and motion control
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    - Constrained kinematics / spherical wrist
    - **Position control** (geometrical control approaches, dynamic decoupling control,…)
    - Force control
  - High dexterity instrument
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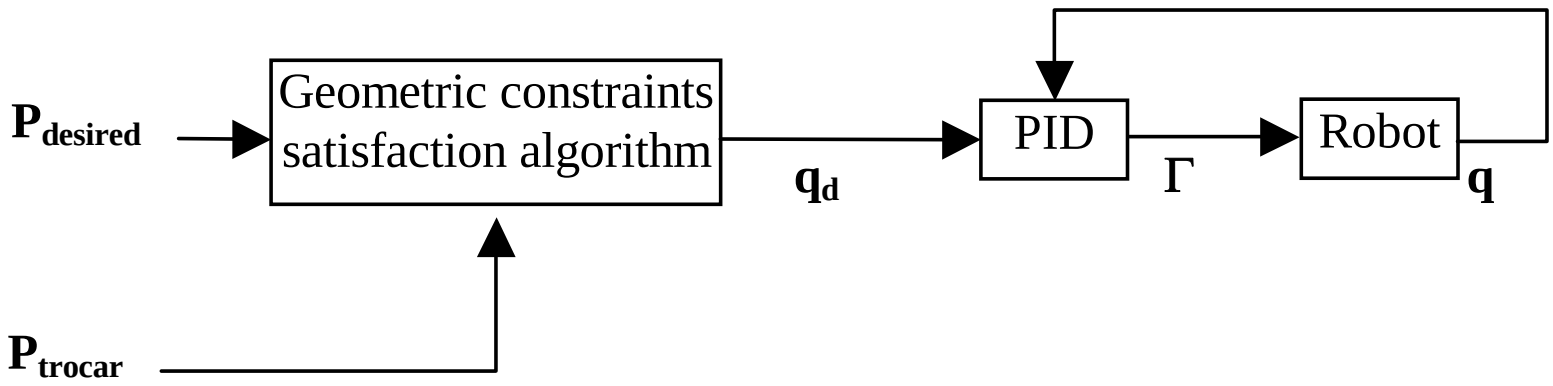
- Teleoperated systems

Option 3 : position control

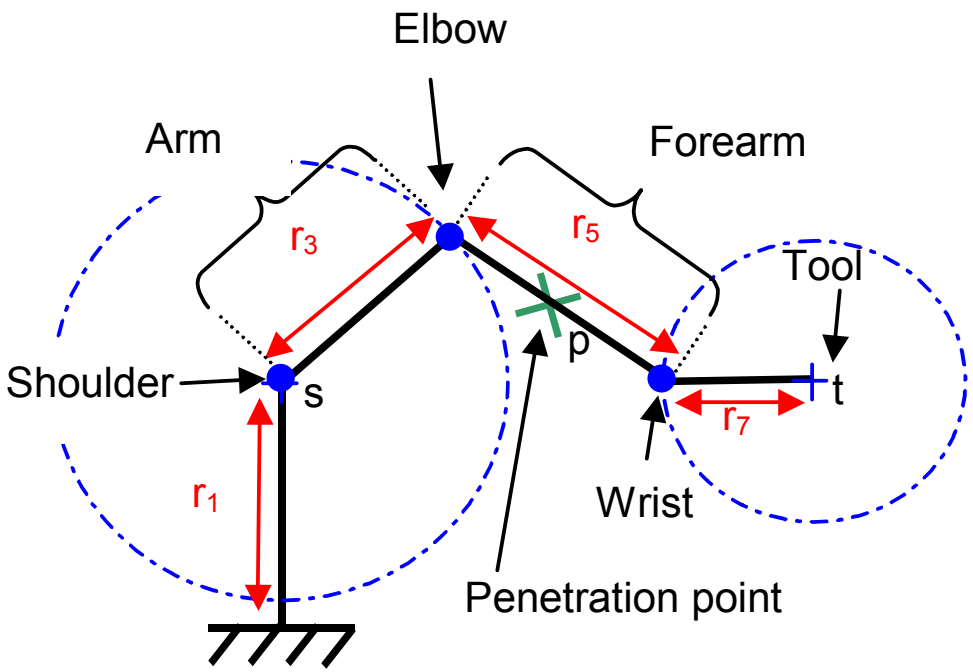
- Geometric constraints satisfaction of the penetration point solved by an optimization procedure [Michelin 04a]



Option 3 : position control

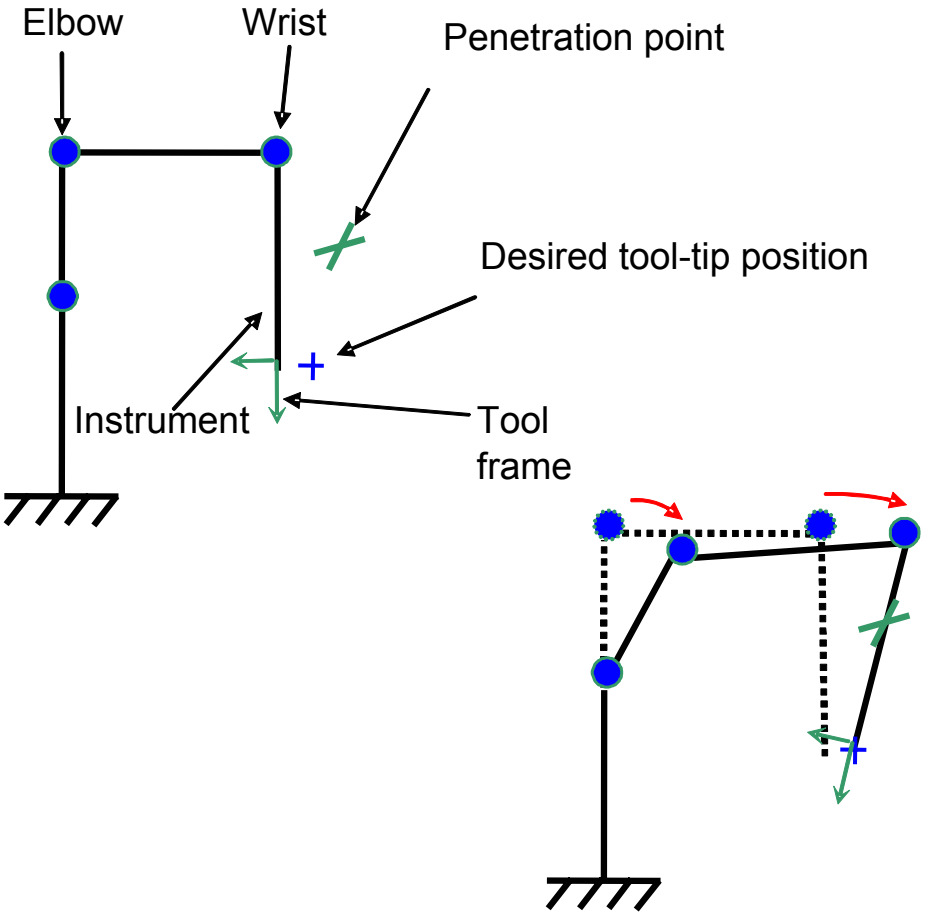
- 1st approach: kinematic dependant [Michelin 04a]

For a desired tool position, the elbow and wrist positions are computed by solving geometrical constraints ensuring the penetration point position.



Option 3 : position control

- 2nd approach: kinematic independant [Michelin 04a]



Description of the constraint in terms of virtual mechanical joint

Dynamic task / posture decoupling [Michelin 04b]

- Background: Khatib's work on **redundant robots** [Khatib 87]

$$\Gamma = \Gamma_{task} + \Gamma_{posture}$$

$$\Gamma_{task} = J^T F$$

External F force acting on the robot

$$\Gamma_{posture} = (I_n - J^T J^{+T})\Gamma_{null}$$

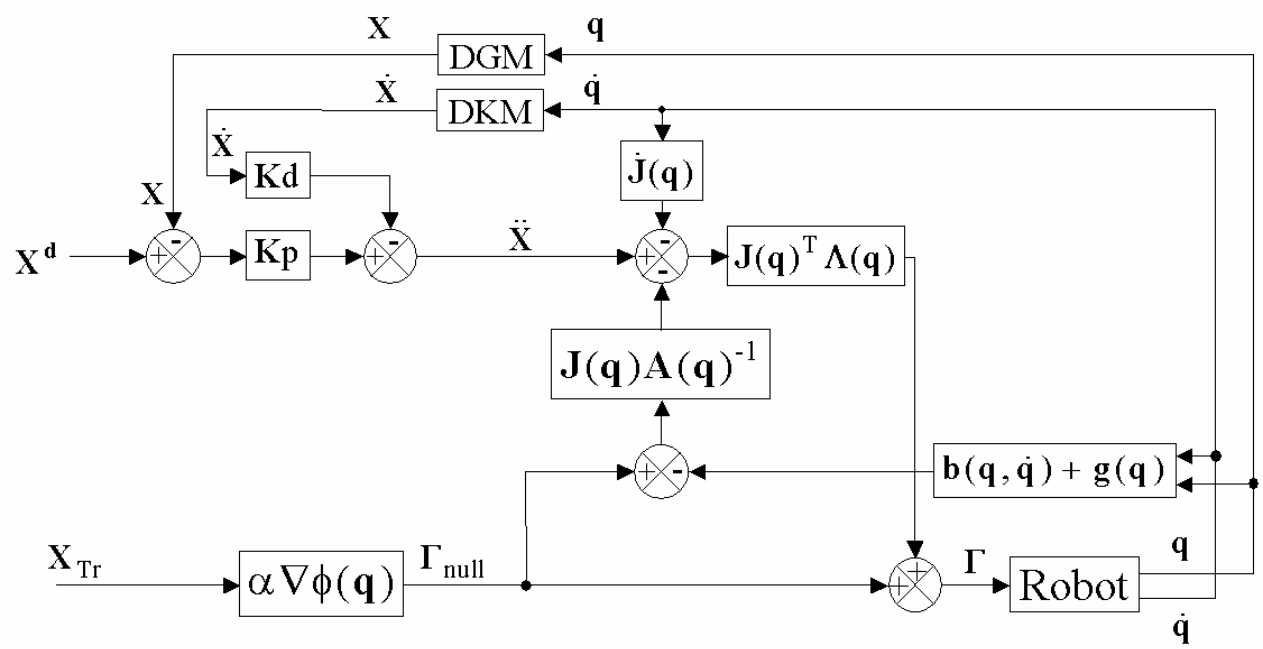
Γ_{null} : arbitrary null space control torque which can be arbitrarily chosen

Dynamic task / posture decoupling

- **Optimization:** Γ_{null} is used to force to zero the distance between the instrument and the trocar or to minimize the contact force applied to the trocar

$$\Gamma_{null} = \alpha \nabla \phi \quad \rightarrow \quad \Gamma = \mathbf{J}^T \mathbf{F} + (\mathbf{I}_N - \mathbf{J}^T \mathbf{J}^{+T}) \alpha \nabla \phi$$

- **Dynamic decoupling control scheme:**



Experimental results

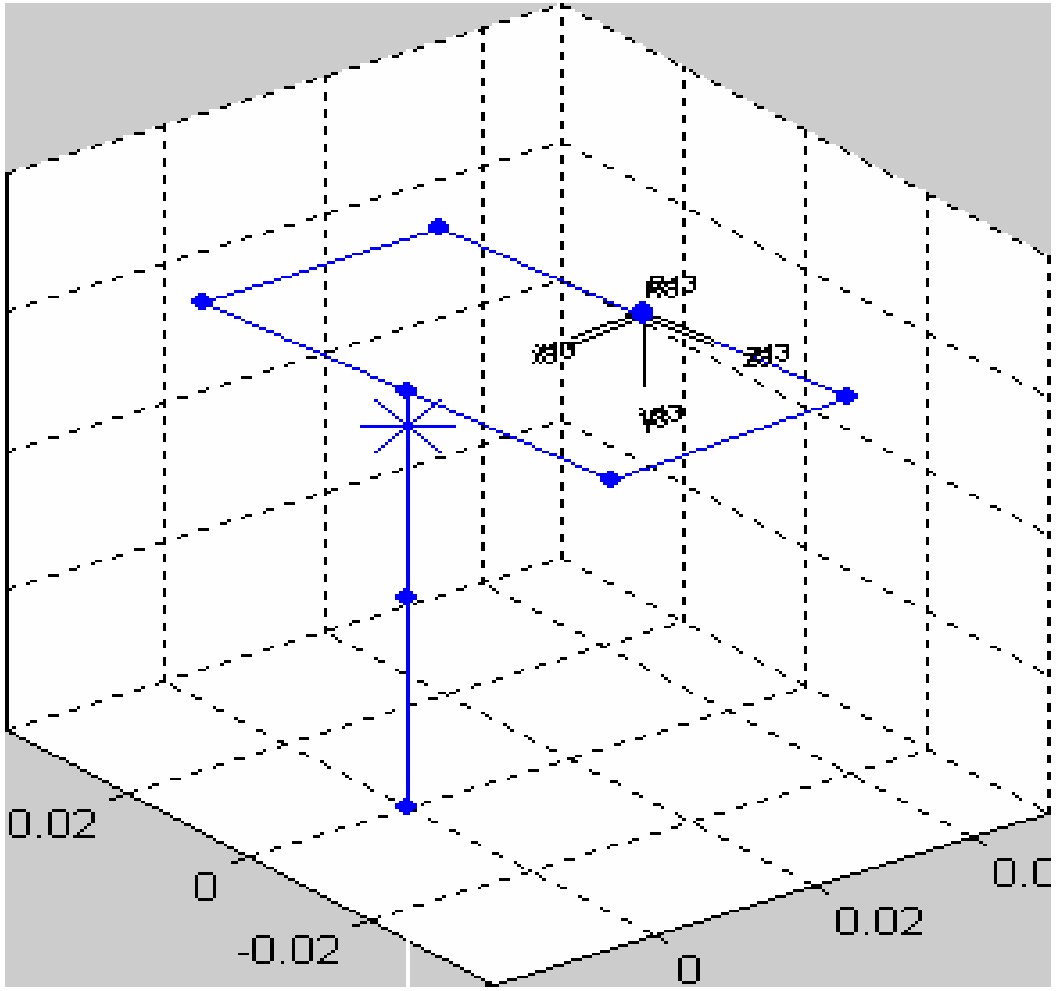
- The algorithm has been implemented on an experimental platform D2M2:
  - A 5-dof slave arm teleoperated by a master arm (Phantom 1.5) through Ethernet link and UDP protocol
  - Equipped with direct drives actuators ➔ high dynamics, low friction
  - F/T sensor fixed at the extremity of the carrier (between carrier and instrument)
  - Controller: Pentium 500 MHz, RTX/ Windows 2000.

- Tested trajectories: straight line, circular and helicoidal paths
- Sample rate: 0.7 ms
- Computing time: 0.35 ms

Experimental results

Perspective: Control of tree redundant structures

Generic algorithm that makes it useable for controlling high dexterity redundant instrument



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Option 4: force control

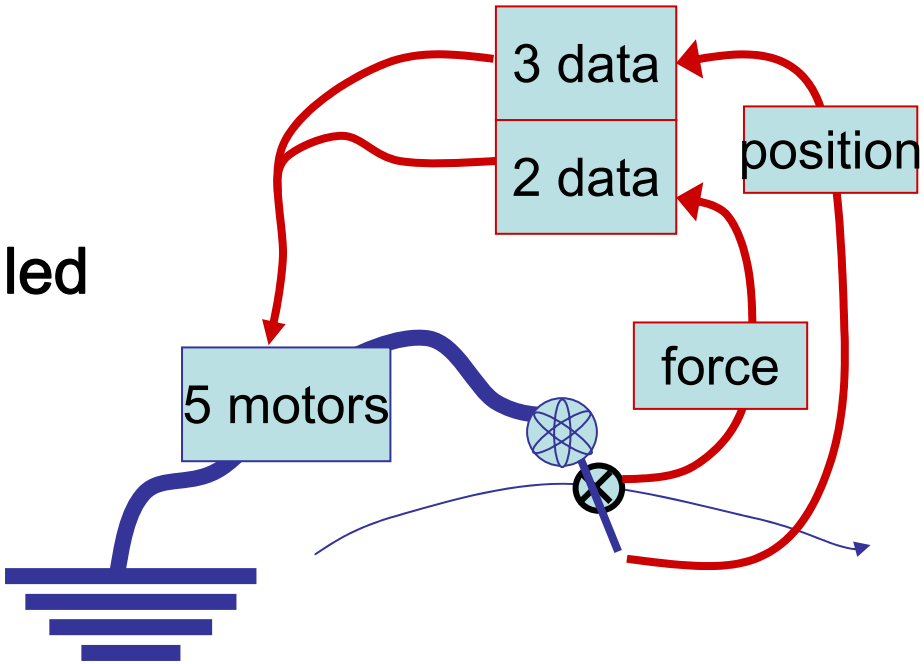
- Mobility ➔ Tx, Ty, Tz ➔ **3**
- **3** = (4 + **5**) – (6 x 1)

5 joints

&

5 motors

2 dof can be controlled with force measurements



(See details in the lecture of G. Morel)

A summary of solutions …

- Option 1 (passive joints)
  - Few motors
  - The trocar “forces” the passive joint to adapt “mechanically”
  - No accurate positioning is needed

- Option 2 (active RCM)
  - Few joints and motors
  - The trocar has no influence on the arm motion
  - BUT, the arm MUST be precisely located (positioning device + procedure)

- Option 3 (spherical wrist)
  - The wrist may require complex parts
  - But it can be easily located on the trocar
  - However it is still rather cumbersome on the patient if the surgeon has to locate 3 of them

A summary of solutions …

- Option 4 (position control)
  - Versatile robot
  - No acurate positioning

- Option 5 (force control)
  - The trocar "forces" the joint to adapt by means of measures + control software
  - A bit more complex

These two options may open a path to "multi-purpose" systems

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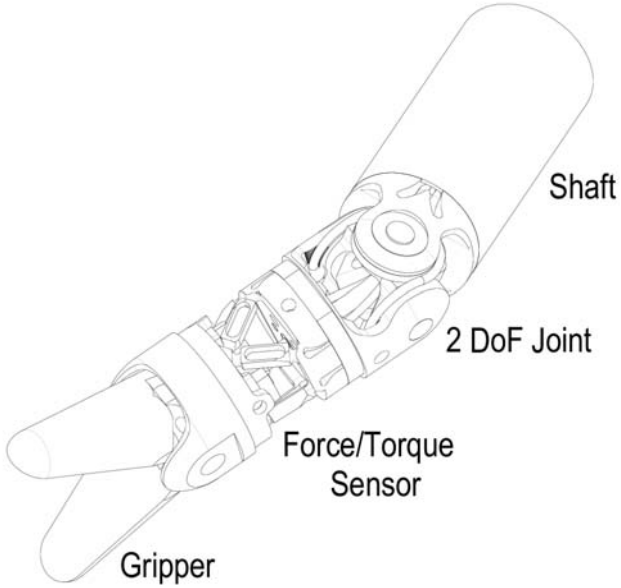
Instrument with high dexterity

- Sensorized and Actuated Instruments for Minimally Invasive Robotic Surgery [DLR, Munich, Germany]



- Full manipulability: universal joint with intersecting axes for twisting the gripper about its longitudinal axis without pivoting the instrument shaft about the point of insertion.

- Prototype diameter: 10 mm

- Range of motion: 40° in both directions.

Instrument with high dexterity

- Manipulation forces: 20 N at the instrument tip

  Gripping force: 20 N.

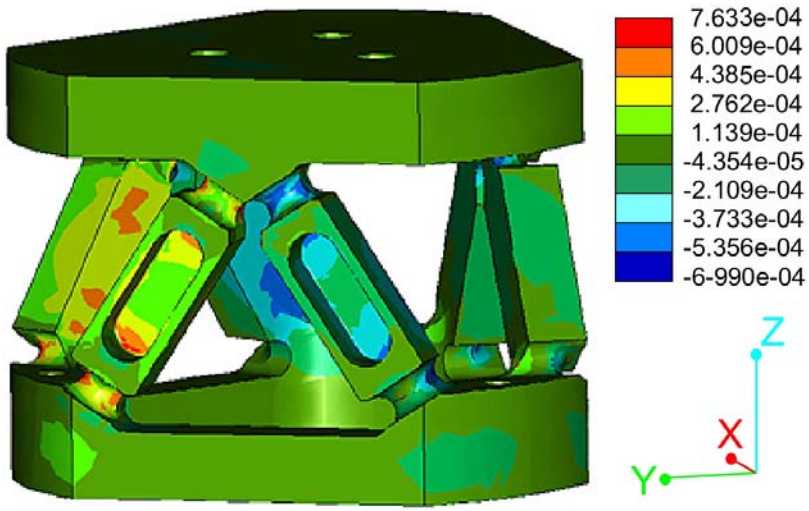
- Gripper actuated by one cable counteracted by a spring.

- The cable force necessary to close the gripper and securely hold a needle: 70 N.

- Maximum driving forces for the joint actuation: 100 N.

- To guarantee zero backlash, the cables are prestressed with the maximal expected driving force, accounting for a worst case cable force of 200 N.

Miniaturized Force/Torque Sensor

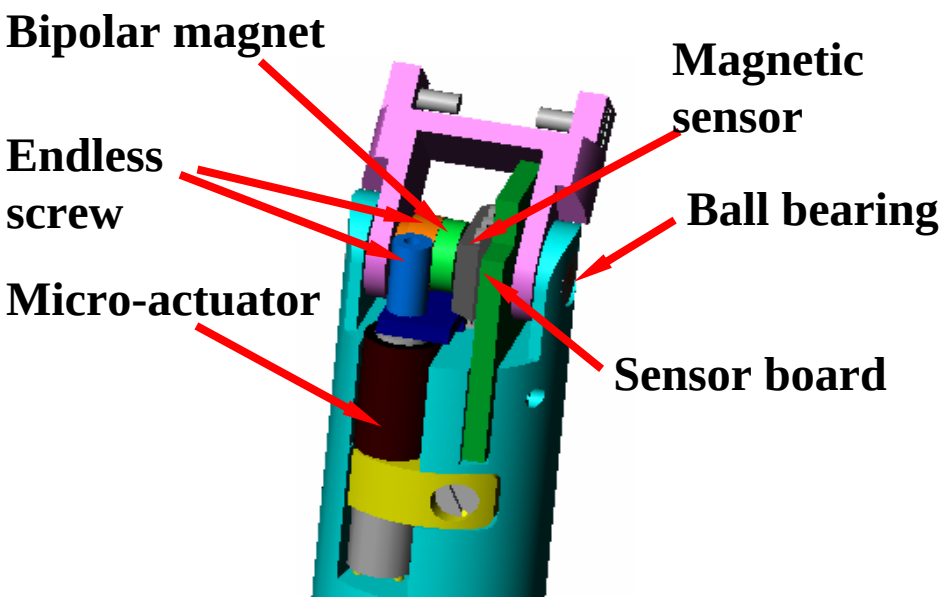


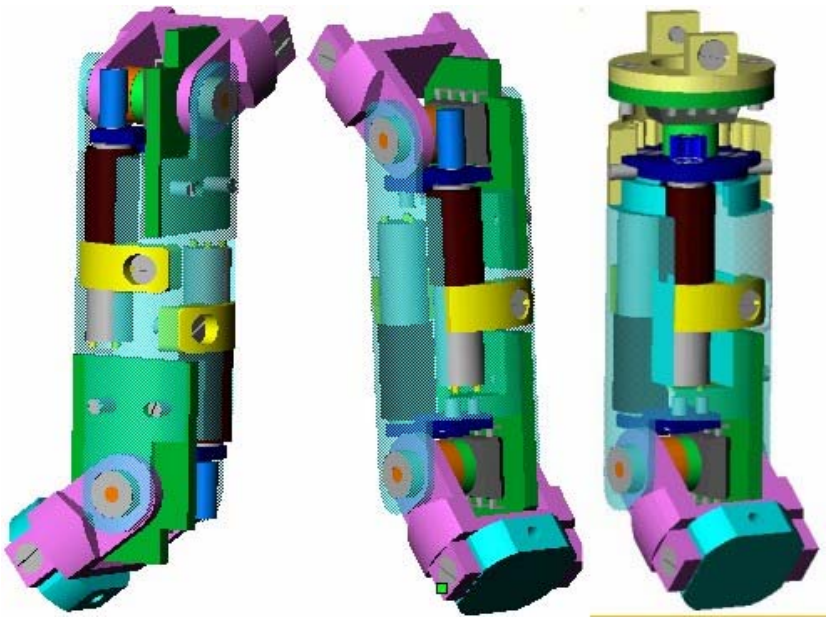
- 6-dof hexapod (high stiffness, adaptable properties, annular shape, scalability) with flexural joints
- Diameter: 10 mm
- Strain gauge sensor
- Forces: +/- 30 N
- Torques: +/- 300 Nmm

Instrument with high dexterity

Modular mechanical design:

- **External Ø = 10 mm ; length = 24 mm (1 dof) and 36 mm (2 dof)**
- **Usefull stroke = ± 90° et > 360° (roll)**
- **Torque = 6 mN.m et 8 mN.m (roll)**
- **Brushless micro-actuators Ø 3 mm**
- **Magnetic resolver -> angular position**

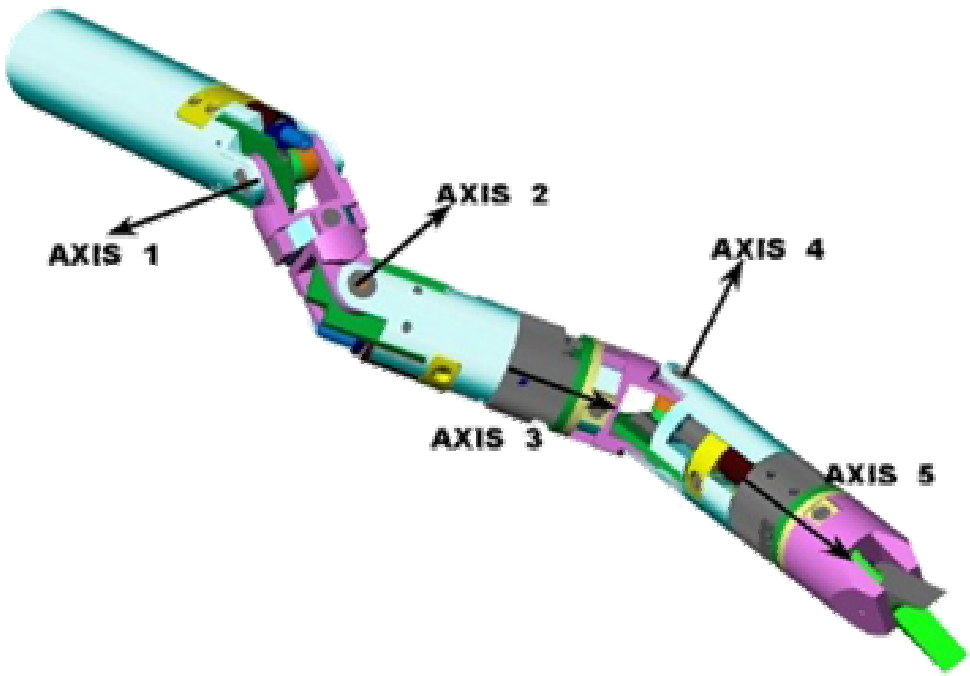




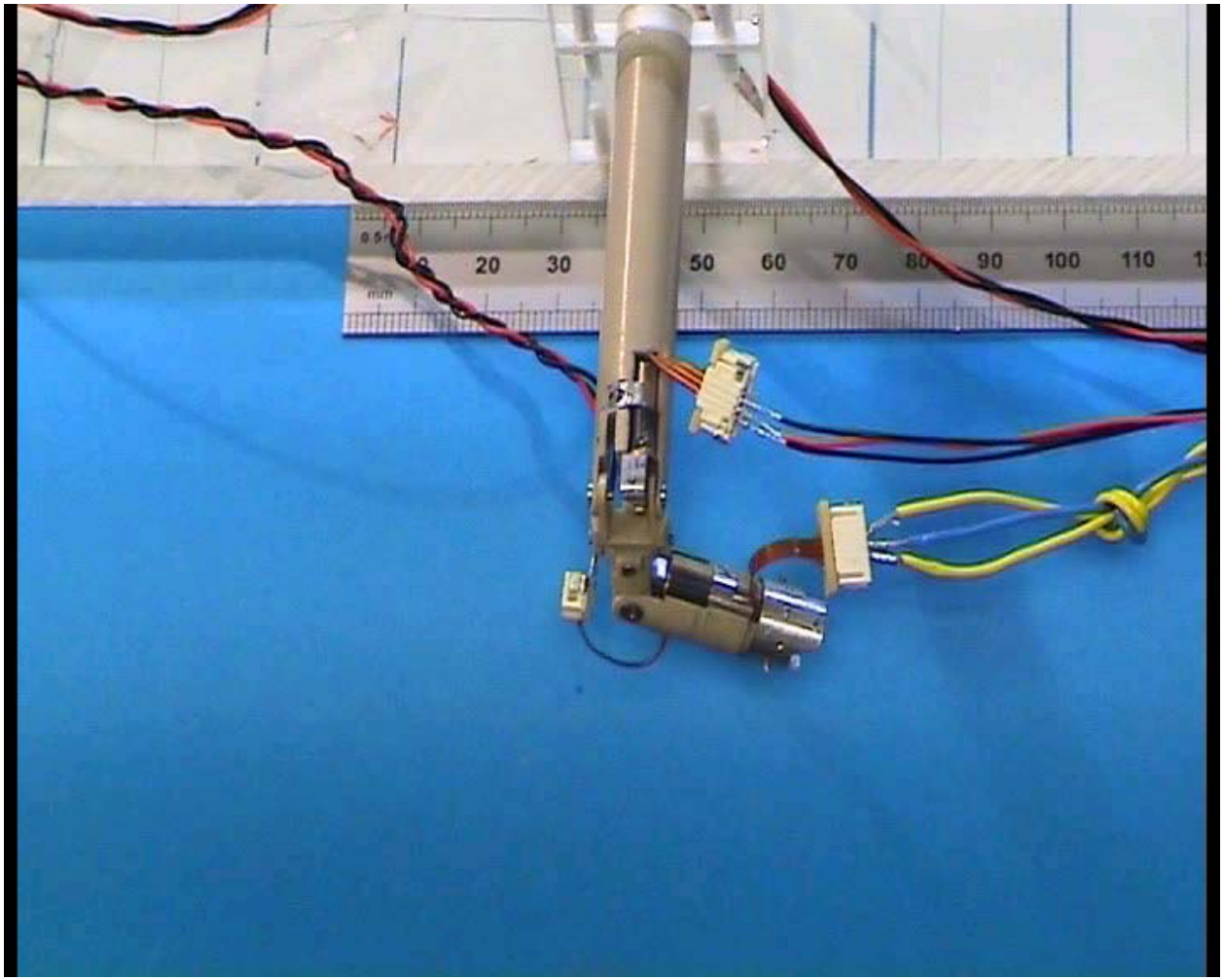
Instrument with high dexterity

Proposed solution:

- **4 modules: 1-dof / 2-dof / 2-dof / Gripper**
- **Total Length = 11 cm**
- **On going manufacturing of the 1st prototype**
- **Module 1-dof: Ø = 1 cm, L = 3,6 cm**

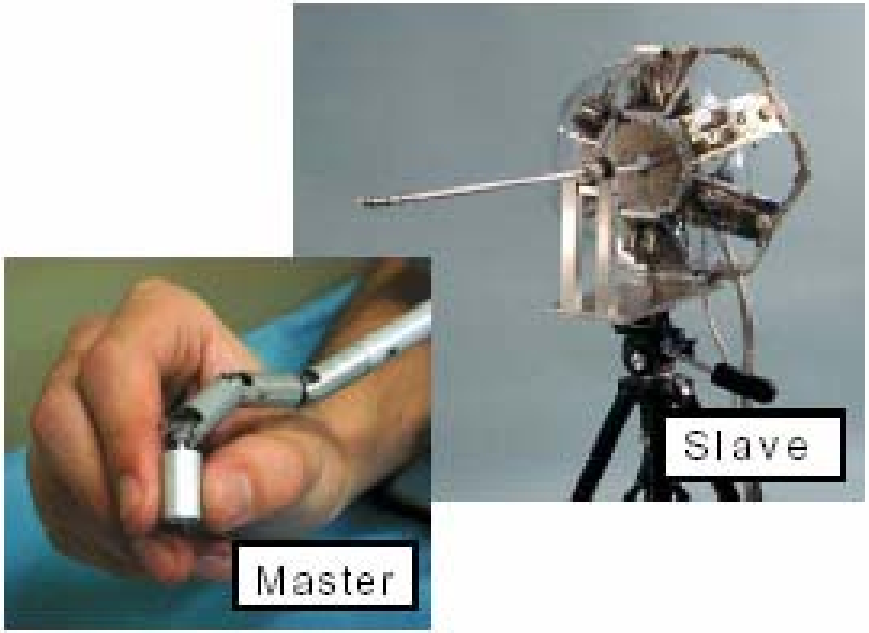


Instrument with high dexterity



Instrument with high dexterity

Hyper redundant miniature manipulator « hyper finger » for remote MIS in deep area [Ikuta 03]



Instrument with high dexterity

- Micro-robot MIPS with 3-dof for endoscopy (2000) [Merlet 00, INRIA Sophia, France]

Diameter 8.6mm, length 2.5cm

Half way to go …

- Motion control
  - Carrier
    - Constrained kinematics / spherical wrist
    - Position control (geometrical control approaches, dynamic decoupling control, predictive control,…)
    - Force control
  - High dexterity instrument
- **Interaction control**
- Teleoperated systems

Bibliography

[Berkelman 03] P. Berkelman, E. Boidard, P. Cinquin, J. Troccaz. LER: the light endoscope robot. *International Conference on Intelligent Robots and Systems*, october 2003.

[Khatib 87] O.Khatib. A unified approach for motion and force control of robot manipulators: the operational space formulation, *IEEE Journal of Robotics and Automation*, RA –3(1): pp 43-53, february 1987.

[Michelin 04a] M. Michelin, E. Dombre, P. Poignet. Geometrical control approaches for minimally invasive surgery. *Medical Robotics, Navigation and Visualization (MRNV'04),* march 2004.

[Michelin 04b] M. Michelin, P. Poignet, E. Dombre. Dynamic task decoupling for minimally invasive surgery motions. *International Symposium on Experimental Robotics (ISER'04)*, june 2004.

[Salle 04] D. Salle, P. Bidaud, G. Morel. Optimal Design of High Dexterity Modular MIS Instrument for Coronary Artery Bypass Grafting. *International Conference on Robotics and Automation (ICRA'04)*, april 2004.

Bibliography

[Hannaford 04] M.J.H. Lum, J. Rosen, M.N. Sinanan, B. Hannaford. Kinematic optimization of a spherical mechanism for a minimally invasive surgical robot. *International Conference on Robotics and Automation (ICRA'04)*, april 2004

[Dombre 04] E. Dombre *et al.*, Design, modeling and control of assistive devices for minimally invasive surgery. *7th International Conference on Medical Image Computing and Computer Aided Intervention (MICCAI'04)*, september 2004.

[Ikuta 03] K. Ikuta, T. Hasegawa, S. Daifu. Hyper redundant miniature manipulator « hyper finger » for remote MIS in deep area. *International Conference on Robotics and Automation (ICRA'03)*, september 2003

[Shoham 03] Shoham *et al.*. Bone-mounted miniature robot for surgical procedures: concept and clinical applications. *IEEE Transactions on Robotics and Automation, vol. 19(5), october 2003*

[Nakamura 2002] Y. Kobayashi, S. Chiyoda, K. Watabe, M. Okada, Y. Nakamura. Small occupancy robotic mechanisms for endoscopic surgery. *International Conference on Medical Computing and Computer Assisted Intervention (MICCAI'02)*, pp.75-82, 2002.

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