Summer School on Cyber-Physical Systems
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Research Director, CNRS

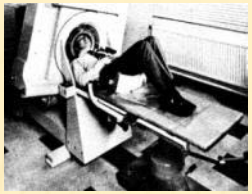
MEDICAL CYBER-PHYSICAL SYSTEMS: THE EXAMPLE OF COMPUTER-ASSISTED MEDICAL INTERVENTION (CAMI)

A FEW WORDS ABOUT TIMC

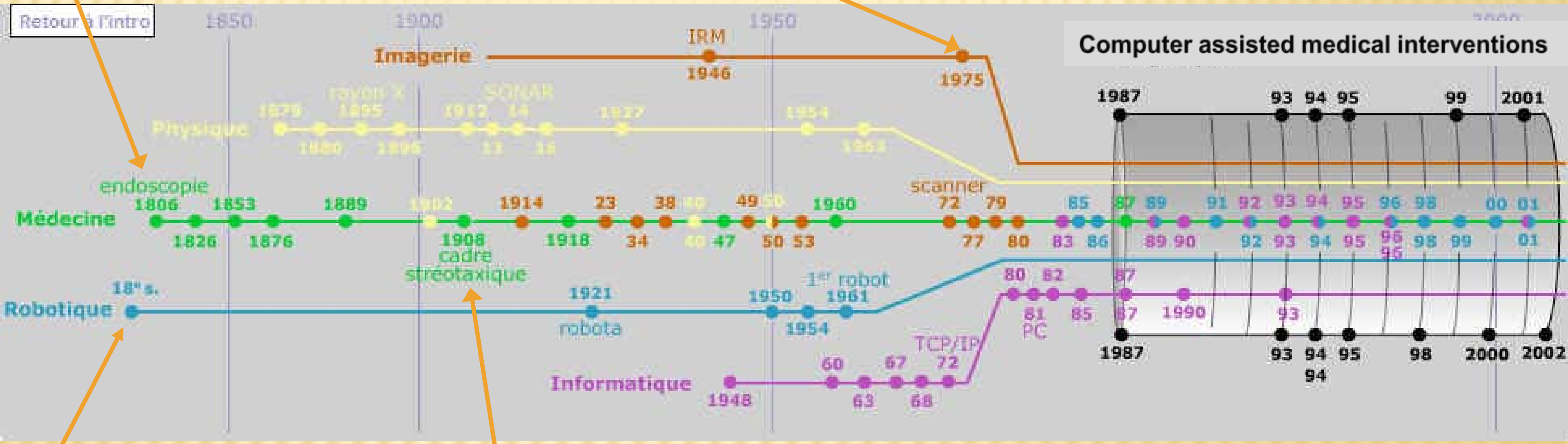
- Located in Grenoble, in the hospital campus
- Created in the early eighties by J.Demongeot (PhD, MD)
- Specialized in « Health applications of maths and computer science »
- A very long story of collaborations with clinicians
- Today:
  - Dir. P.Cinquin (PhD, MD)
  - 230 people (medicine, informatics, signal, maths, statistics, biology, epidemiology, etc.)
  - 10 teams (my team = CAMI = 35 people)
  - More that 15 companies created from the lab and more than 60 intenational patents

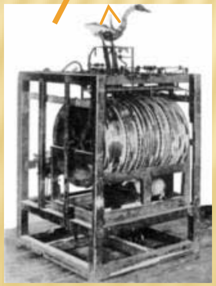
CAMI HISTORICAL PERSPECTIVE

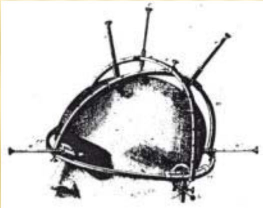
[Bozzini]



[Hounsfield]





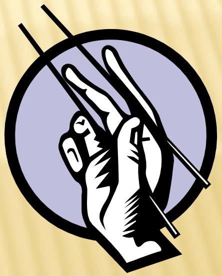
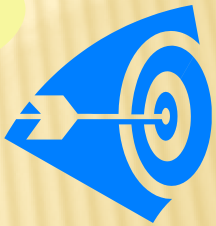


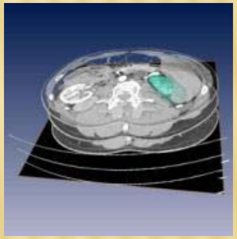
Zernov1890

[Leksell]

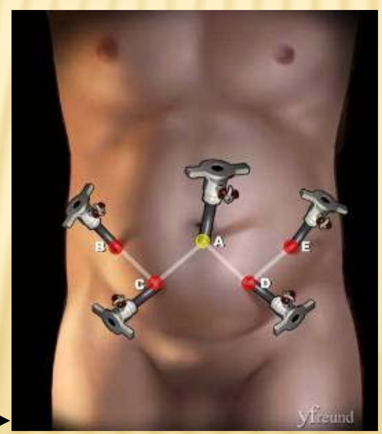
CLINICAL MOTIVATION

- Minimal invasiveness
  - Less perception
  - Less dexterity
  - Smaller targets
- More and more information
  - 2D, 3D, 4D, projective
  - Anatomy/function
- Quality insurance and legal issues
- Many actors

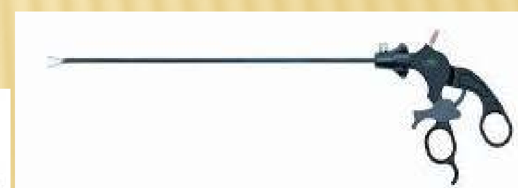






ENDOSCOPIC TECHNIQUE

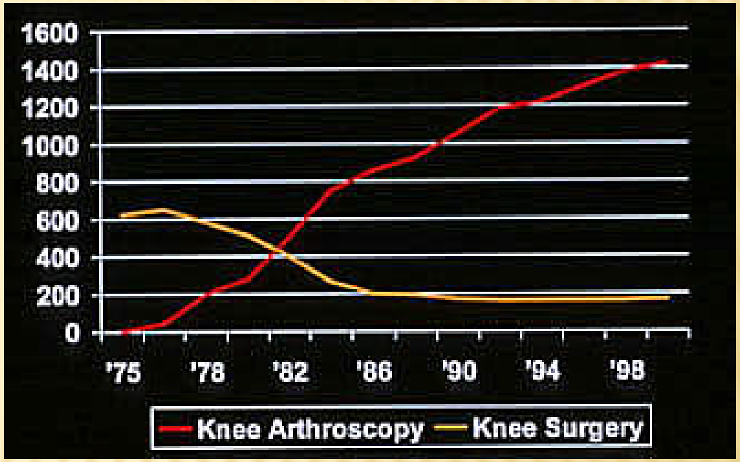


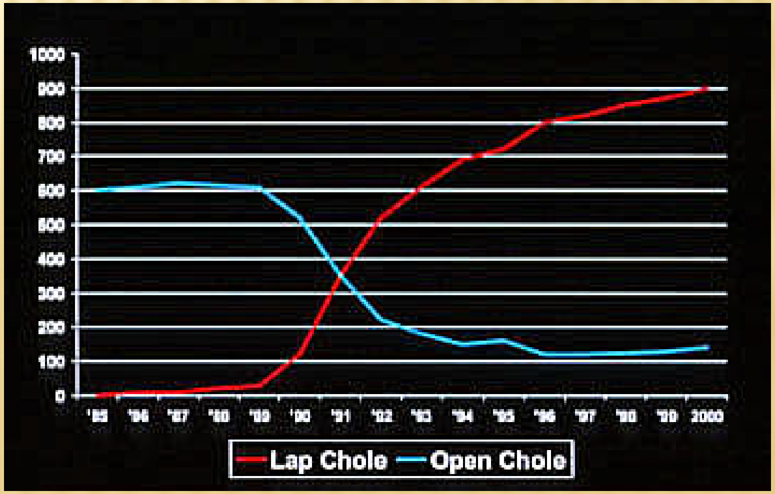
ex. radical prostatectomy



EVOLUTION OF TECHNIQUES

- Two examples:
  - Knee arthroscopy
  - Laparoscopic cholecystectomy

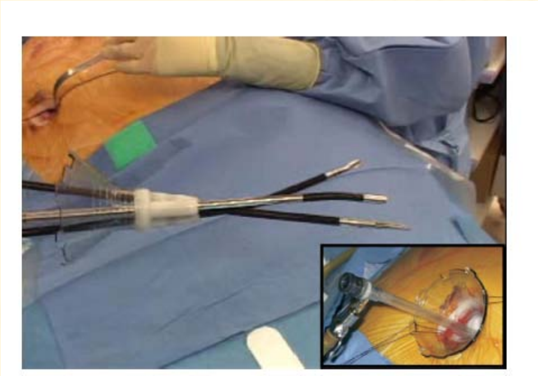




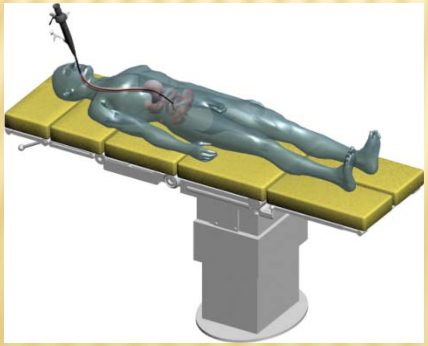
Source: Computer Motion

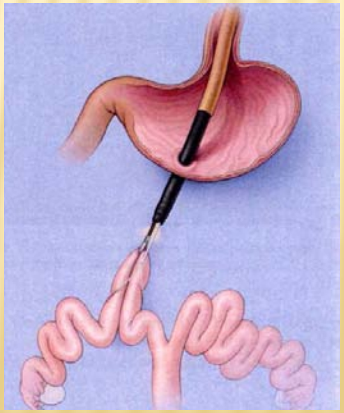
MORE RECENTLY

- Single port



- NOTES (Natural Orifice Transluminal Endoscopic Surgery)





ANOTHER TYPE OF NEED

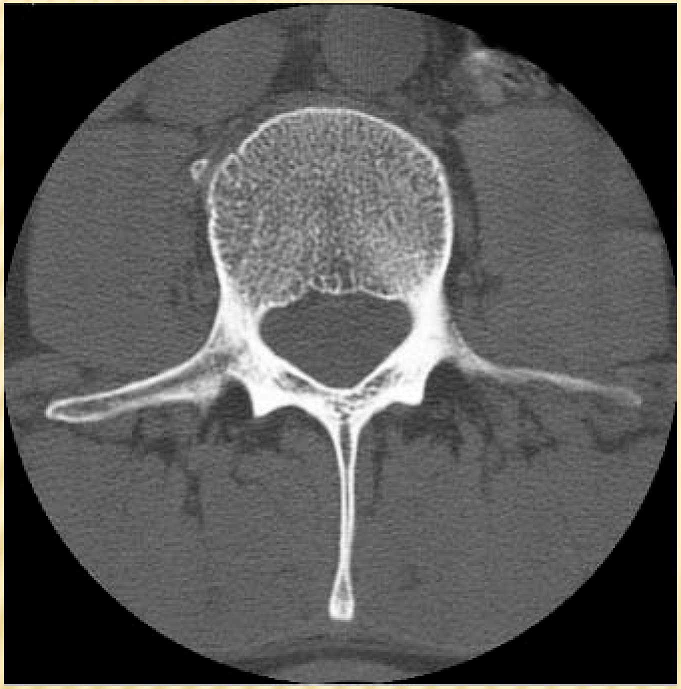
A/P X-ray, patient standing up

COOB angles :
T5-T11 = 40°
T11-L4 = 32°

A/P X-ray, patient standing up

COOB angles(after surgery):
T5-T11 = 8°
T11-L4 = 10°

WHY IS IT DIFFICULT?



- 10% to 40% misplaced screws

Misplaced screws may result in neurological disorders or vascular damages

- How to transfer the planning to the intra-operative conditions ?

THESE TWO TYPES OF APPLICATIONS…

- … require:
  - 1st case: recovering the perception and dexterity (and compensating organ motions)
  - 2nd case: transferring the planning from the clinician mind/computer to the real patient

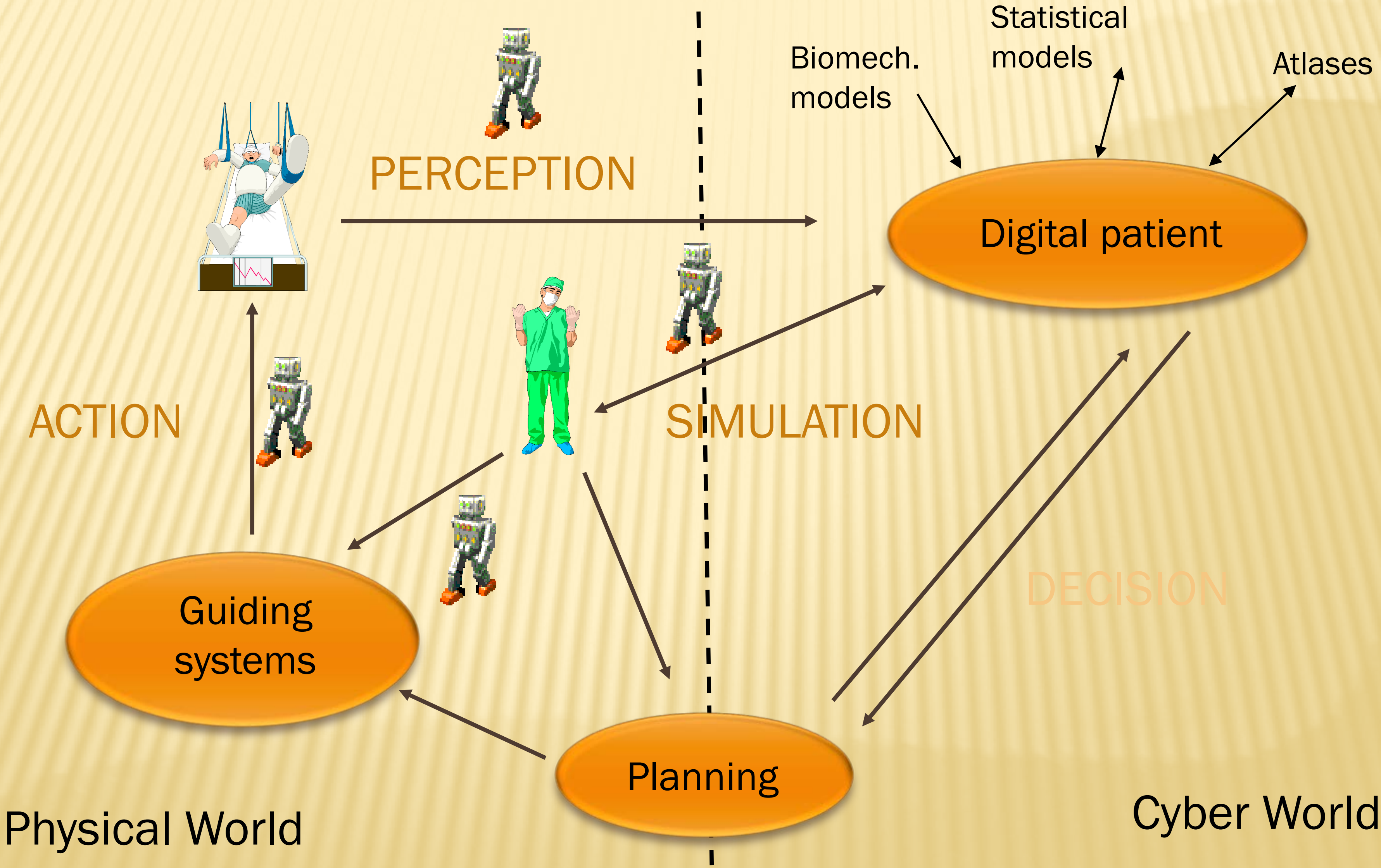
WHAT IS CAMI?

- Objective of CAMI:

  To help the clinician for the planning, simulation and execution of safe, efficient and minimally invasive diagnostic or therapeutic actions

- Scientific issues:
  - Image and signal processing
  - Data fusion
  - Models (action, patient, disease, etc.)
  - Simulation (procedure, patient, organ, etc.)
  - Assistance (robot/navigation)
  - Man-machine interface

WHAT IS CAMI?

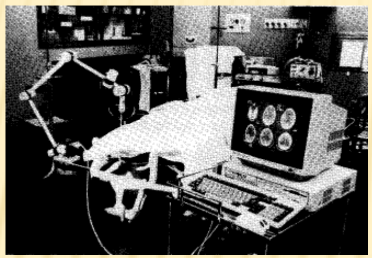


Statistical models
Biomech. models
Atlases
PERCEPTION
Digital patient
ACTION
SIMULATION
DECISION
Guiding systems
Planning
Physical World
Cyber World

TYPES OF GUIDING SYSTEMS

- Passive systems : give information about the on-going procedure w.r.t. planning
  - Surgical navigation

[Watanabe87]



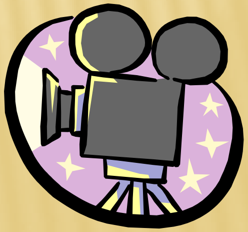
Imactis,
CHU Grenoble

- Active systems: execute part of the action
- Semi-active systems : physical guidance
- Interactive systems
  - Co-manipulation →
  - Tele-operation

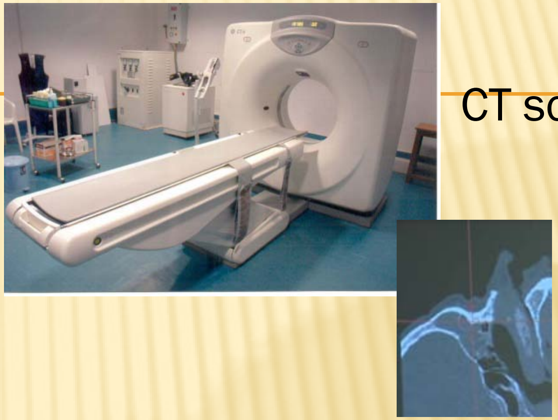
RIO system, Mako Inc.

SURGICAL NAVIGATION: ONE EXAMPLE

- Computer-aided endonasal surgery (TIMC, PRAXIM, CHU Grenoble)
  - Pre-operative imaging (CT scan)
  - Intra-operative stage:
    - Data acquisition (skin palpation)
    - Intra-op/pre-op data registration (optimization process)
    - Visualizing the tool pose relatively to CT data
- Video



THE ENTACT SYSTEM

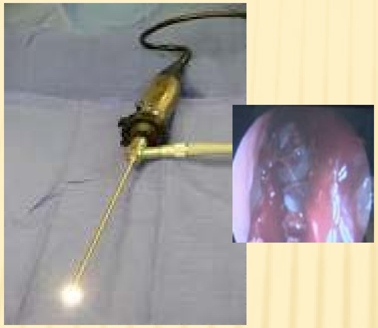


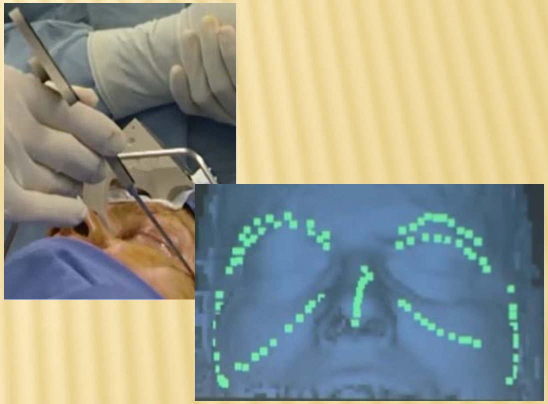
CT scan

Sensors

localizer

endoscope





registration

Sensorized instruments

Decision making

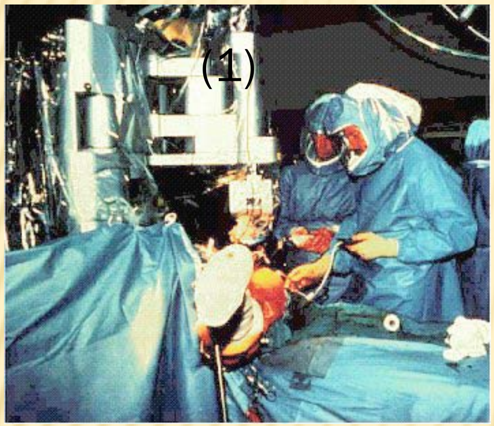
Caregiver

A ROBOT: WHAT FOR?

- A perfect cyber-physical interface
- Linked to patient data
- For:
  1. Complex tasks
  2. Handling heavy sensors/instruments
  3. As a third hand
  4. Remote action
  5. Improved resolution (motion, force)
  6. Automated tracking
  7. Intra-body actions

EXAMPLES

ROBODOC (1)



(2) Surgiscope

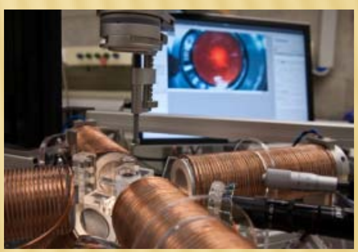
Da Vinci (3,4,5)

(3)

ViKY

Cyberknife (1,2,6)

(7,5)



Aeon Scientific

FIRST STEPS

- Stereotactic neurosurgery
  - Long story of target localization from measurements
  - 3D imaging

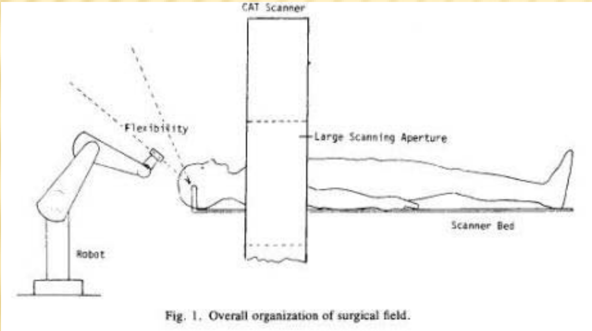
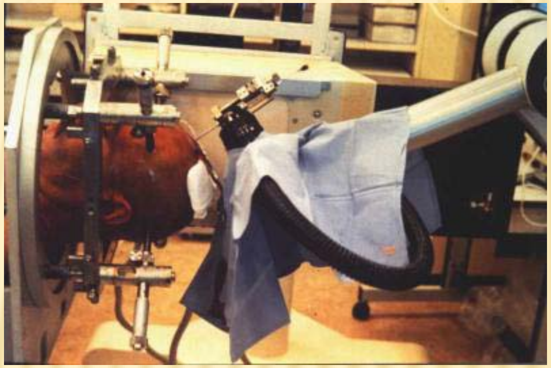
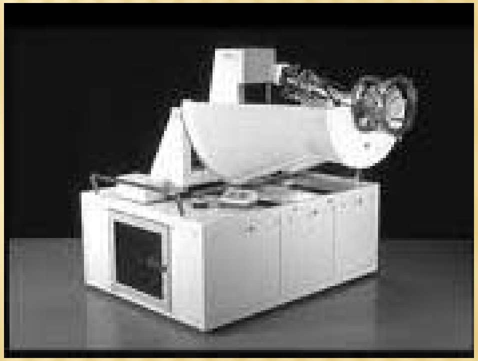


Fig. 1. Overall organization of surgical field.

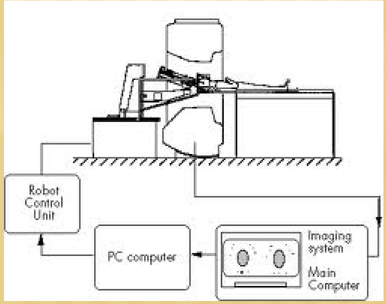
[Kwoh et al,
IEEE TBME1988]
about22 patients



[Lavallée, Cinquin,
Benabid 1989] - Neuromate
Thousands of patients

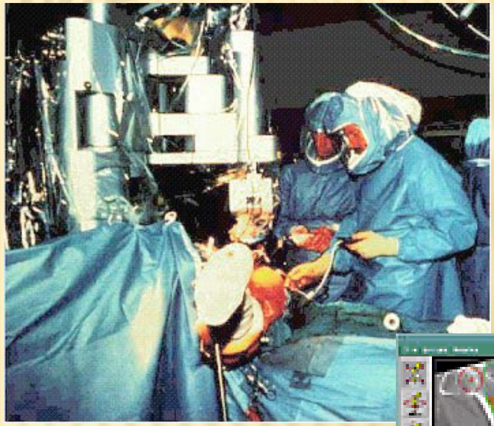


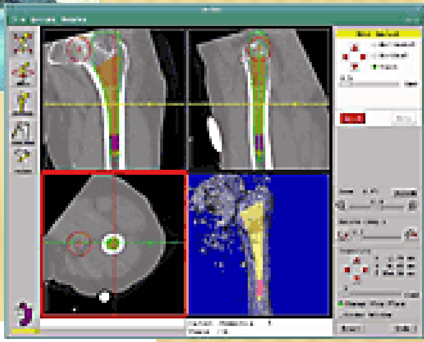
[Glauser et al,
EPFL1993] <10 patients

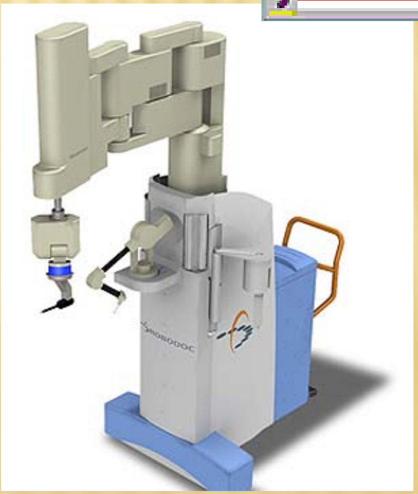


ORTHOPEDIC APPLICATIONS

- Still a « manufacturing » view of robotics
- Bone surface preparation for prosthetic surgery
- A pioneer system ROBODOC (IBM [Taylor et al.] then ISS then …)
- 1st patient in 1992 then tens of thousands of patients







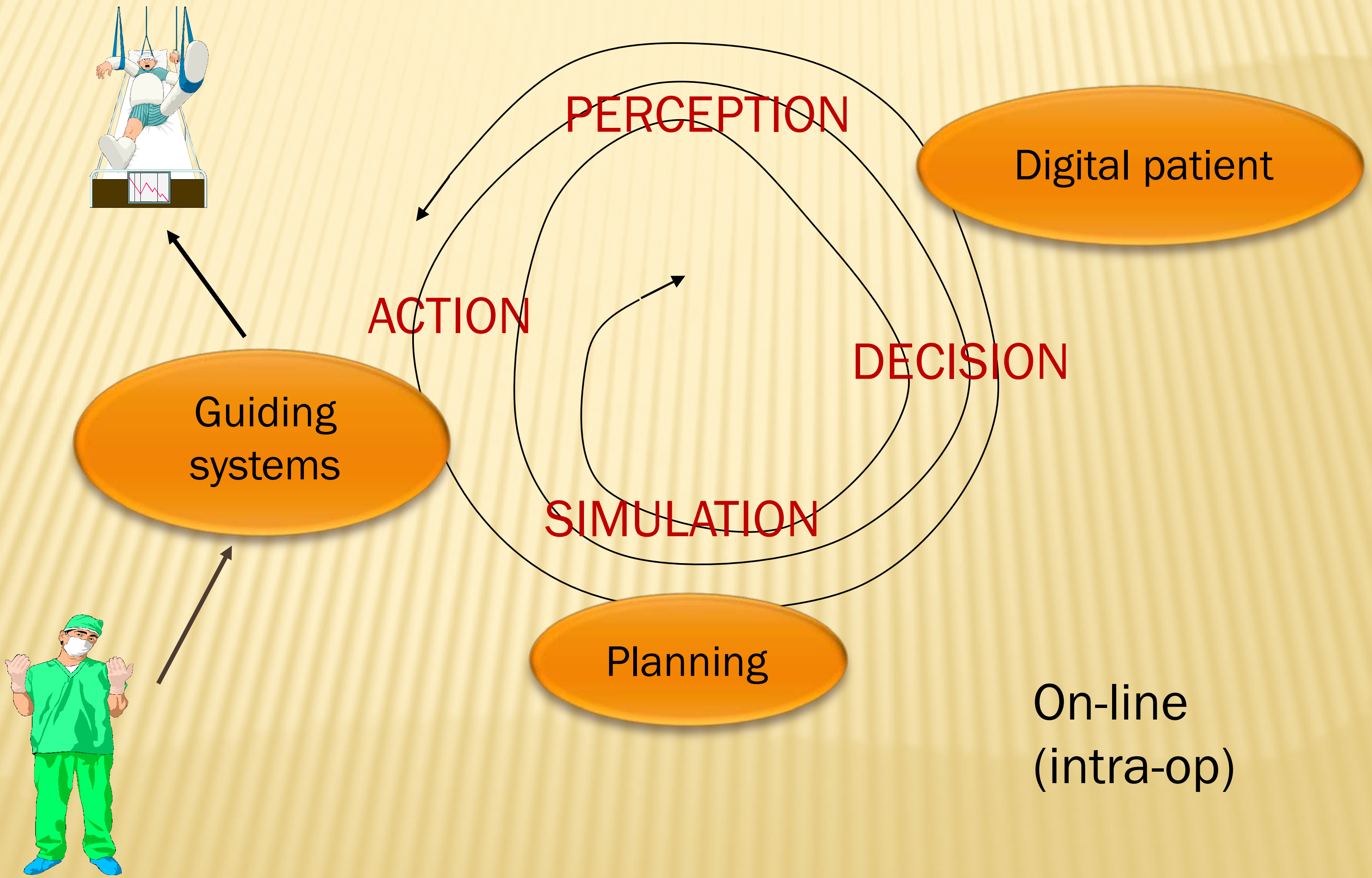
FROM RIGID TO SOFT TISSUES

- Difficult automation for mobile and deformable structures
- Tele-operation approach
  - Endoscope holder (AESOP, Computer Motion Inc.) 1994
  - Instrument holder (ZEUS, CMInc, DaVinci Intuitive Surgical Inc.)

MOBILE AND DEFORMABLE TARGETS

- Movements and deformations due to
  - Physiological activity (lungs, heart, bladder, etc.)
  - Vicinity of moving organ (kidney, prostate, etc.)
  - Patient position (breast, etc.)
  - Action on the organ (puncture, US acquisition,etc.)
  - Combination (breast, prostate, etc.)
- Predictable or not? Time scale?
- Requires
  - Models when possible
  - Tracking (images/signals)
  - Synchronization (discrete/continuous)

CAMI FOR SOFT TISSUES



NEW TRENDS

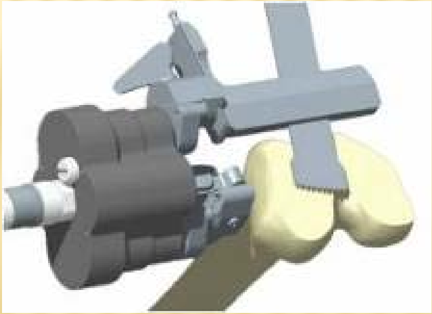
- Perception
  - Real-time acquisition, processing
- Reasoning
  - Real-time registration
  - Model for planning and update
- Action
  - « Compliant » robots (move with the target)
  - Tracking abilities

BODY-SUPPORTED ROBOTS

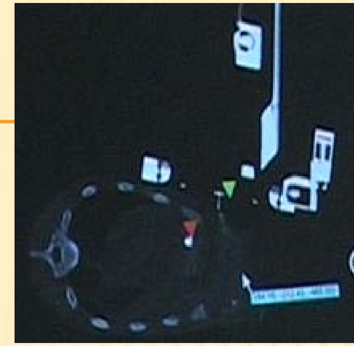
- Move with the patient/structure
- Small workspace
- Close to the surgical site
- Required asepsis
- Examples:
  - On-bone: MARS/MAZOR, Praxiteles/iBlock, etc.
  - On-body: LER/Viky,TER, LPR, CT-Bot (ICube, Strasbourg), MC^{2}E (ISIR, Paris)

MARS / MAZOR
(Technion, Israel)

PRAXITELES/iBlock
(PRAXIM-TIMC, France)



Tele-operated
(voice)



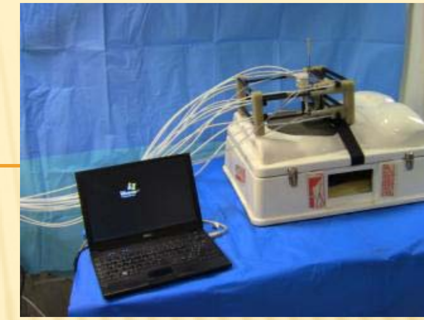
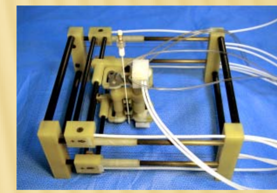


Image-guided

LPR (CT and MRI compatible)
TIMC, France



LER -ViKY
TIMC, Endocontrol Medical
France

TER
TIMC, France

Tele-operated
(haptics)

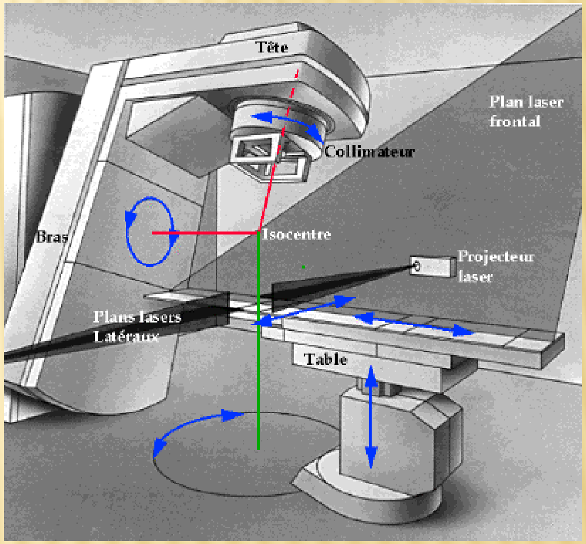
AUTOMATED IMAGE-GUIDED CONTROL

- Off-line planning: get image, plan, get image, register, execute
  - Robodoc for instance.
- On-line (interventional procedures): get image, plan, execute
  - Puncture robots (CT, MR, US-based) – ex: JHU's robots, LPR , Prosper (TIMC), CT-Bot (Strasbourg)
- Closed-loop: plan, [get image, update plan, execute]*
  - Real-time registration (ex: Cyberknife)
  - Visual servoing (ex: UBC Salcudean's tele-echo robot)

CYBERKNIFE V1 [SCHWEIKARD ET AL.]

- Radiotherapy application
- Complex trajectories for improved tumor destruction (multiple radiation ports)
- 6 DOFs required
- Very heavy tools

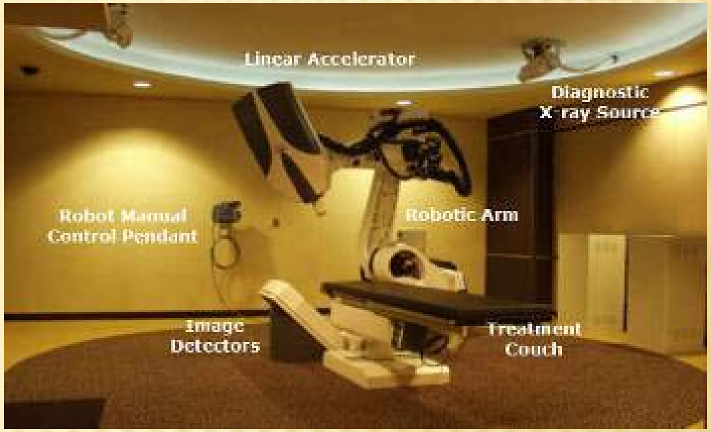
Traditional linear accelerator set-up



LINAC linear accelerator for stereotactic radiosurgery--the CyberKnife (TM). (C) Copyright 2000 IGL and AccuRay.

CYBERKNIFE+SYNCHRONY

- Pre-op: planning on CT data
- Intra-op: a robot, two X-ray sensors, a localizer
- Developed methods:
  - X-Ray/robot calibration
  - X-Ray/DRR registration for head motion compensation
  - Or fiducial-based registration plus real-time tracking for targets moving with respiration



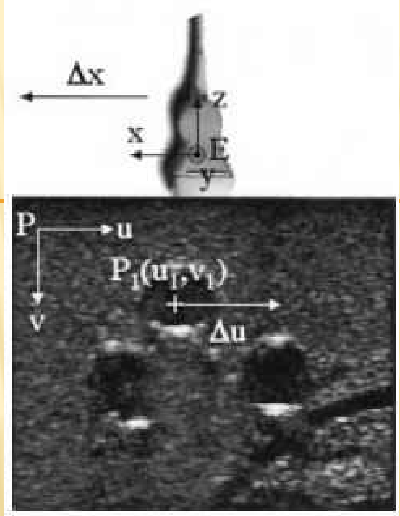
Cyberknife V2

Cyberknife V3+ RoboCouch

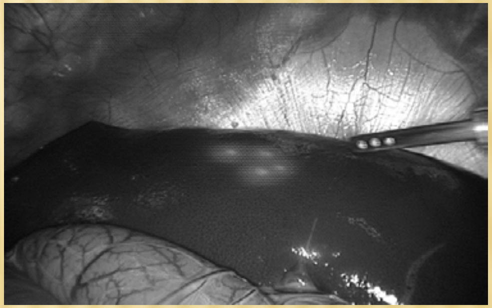
REAL-TIME REGISTRATION

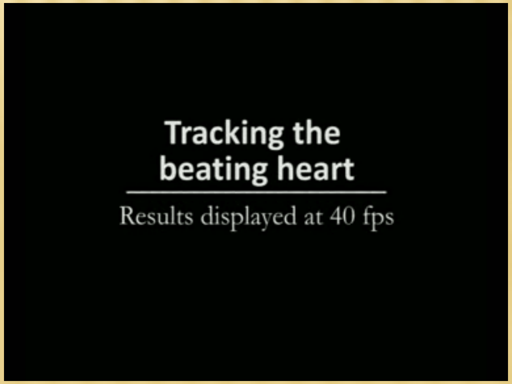
- Conventional way of dealing with respiratory motion in radiotherapy
  - Enlarge target volume to include inspiration and expiration
  - Gating: synchronize radiation delivery to a phase (e.g. full expiration)
- Move with the target [Schweikard05]
  - Internal fiducials (gold seeds) for initial registration
  - External fiducials (IR diodes) for respiration tracking
  - Learning internal/external fiducials relationship

VISUAL SERVOING



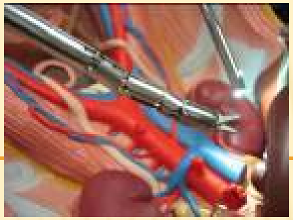
- Ultrasound tracking of arteries (UBC, Salcudean et al.)
- Synchronizing a modified endoscope / instr. to breathing or to the beating heart (DeMathelin et al., ICube lab)
- Heart motion compensation
  - High dynamics
  - Pionneering work in 2001 from Nakamura et al
  - Tracking image natural features



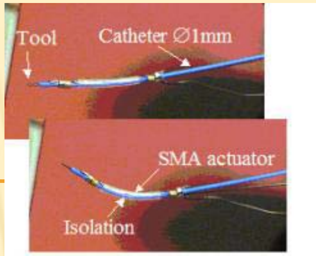


Courtesy: P.Poignet, LIRMM, France

A NEW SCALE



[Tokyo Univ.]



[ISIR lab, Paris]

- Active catheters/endoscopes
  - Adapt to the structure curvature/ more DOFs / NOTES
- Other intrabody robots
  - Coloscopy application
  - Locomotion on organs (heart, liver, etc.)
  - Intra-occular surgery
- Already clinically available: “smart pills”
- Challenges: biocompatibility, power supply

[Dario et al. SSSA]

[Rivière et al. CMU]

[Nelson et al. ETHZ]

Given Imaging