Robot registration

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http://www-timc.imag.fr/gmcao
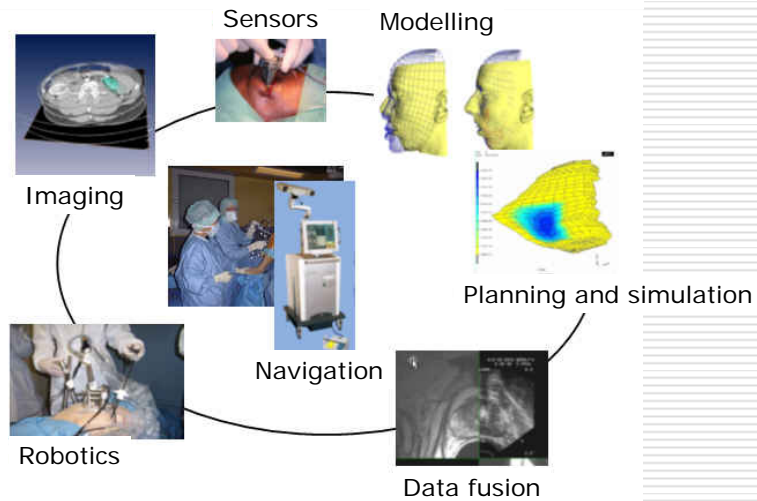http://www-timc.imag.fr/Jocelyne.Troccaz

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Grenoble GMCAO (CAMI) team

- ☐ Created in 1985 by Philippe Cinquin
- ☐ Headed from 1996 by Jocelyne Troccaz
- ☐ Strong connection to Grenoble Hospital
- ☐ About 35 people

Grenoble

We are there   Grenoble Hospital

Research topics

Sensors   Modelling

Imaging

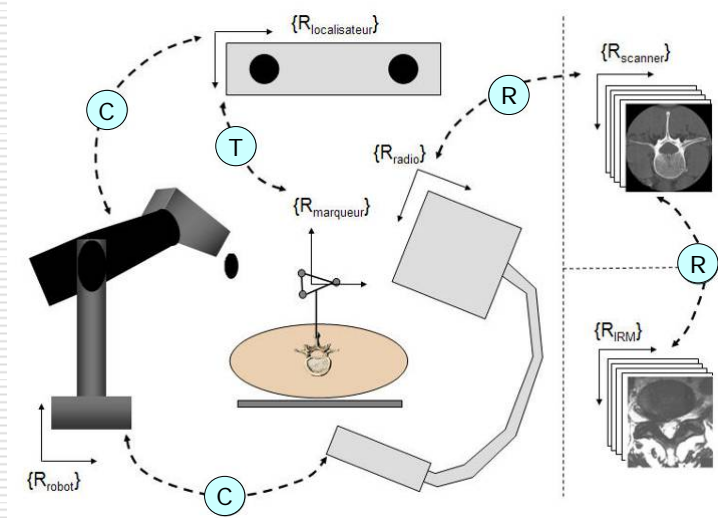Planning and simulation

Navigation

Robotics

Data fusion

What is it?

☐ Registration consists in determining geometric relationships between two reference frames

☐ Robot registration essentially consists in transferring the planning to the robot coordinate system

Intra-operative data

Image registration

Pre-operative data

?

?

Robot

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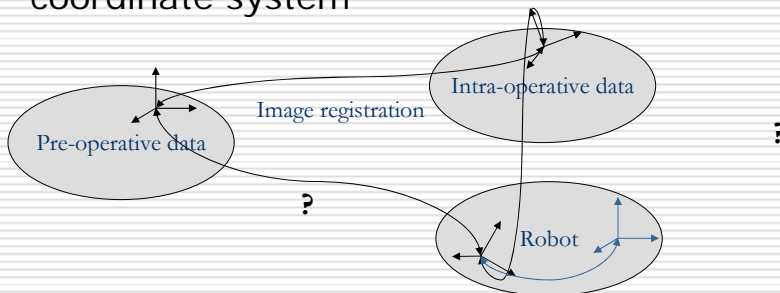
Example

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Tools

☐ Calibration
☐ Tracking
☐ Data registration
Using:
☐ Patients' data
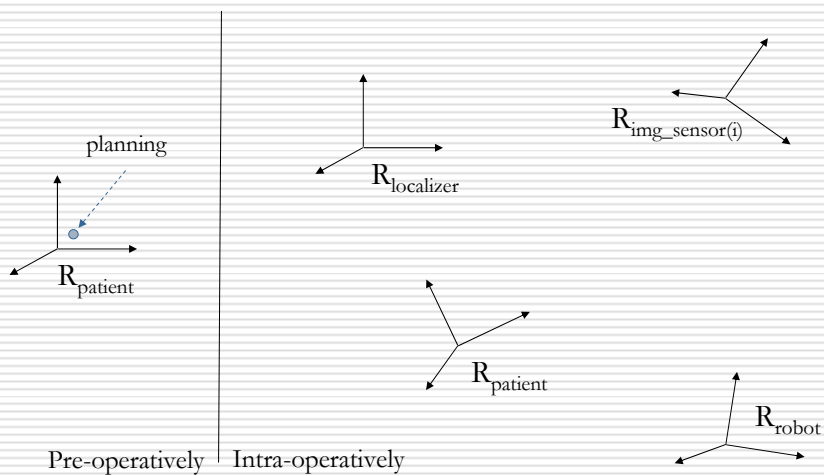☐ External objects
Requires
☐ Intrinsic robot calibration
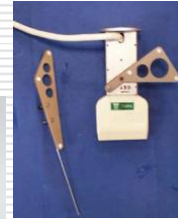
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Contents

- ☐ Introduction
- ☐ Methods
- ☐ Examples: four main situations
- ☐ Conclusion

Possible reference frames of interest

planning

$R_{img\_sensor(i)}$

$R_{localizer}$

$R_{patient}$

$R_{patient}$
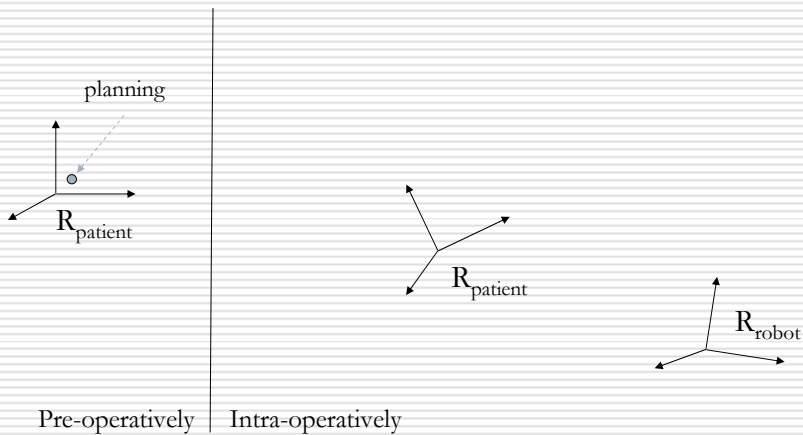
R_{robot}

Pre-operatively | Intra-operatively

Hardware examples

- ☐ Localizers:
  - ■ Optical, US, magnetic, mechanical arm
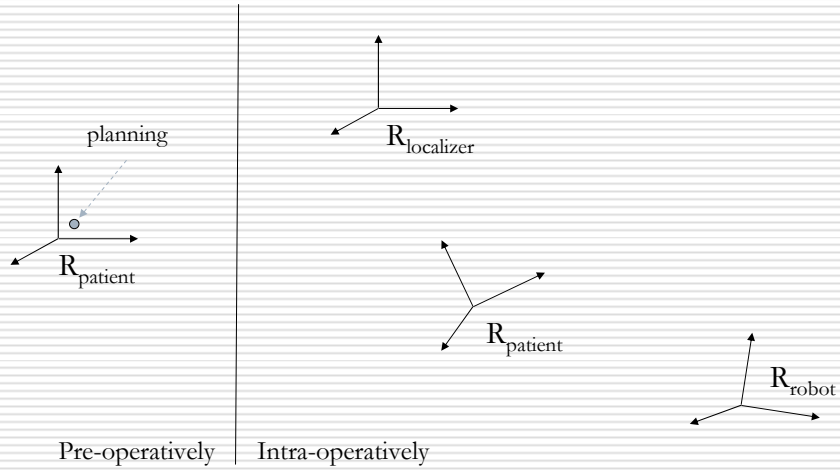- ☐ Imaging sensors:
  - ■ Fluoroscopy, digital X-Ray, ultrasound

Examples A:
Robodoc, ACRobot, (CAD-Implant)

planning

$R_{patient}$

$R_{patient}$

R_{robot}

Pre-operatively │ Intra-operatively

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Examples B: CASPAR

planning

$R_{localizer}$

$R_{patient}$

$R_{patient}$

R_{robot}

Pre-operatively | Intra-operatively

Examples C:
Speedy, Cyberknife, MARS
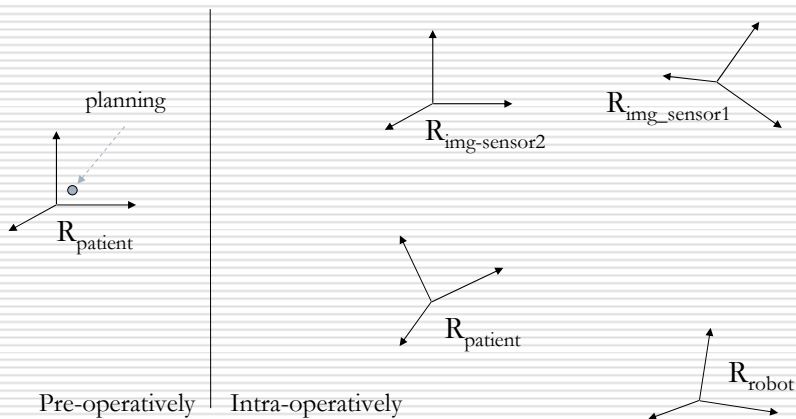
planning

$R_{img\text{-}sensor2}$

$R_{img\_sensor1}$

$R_{patient}$

$R_{patient}$

R_{robot}

Pre-operatively | Intra-operatively

Example D: Cyberknife+Synchrony

planning

$R_{patient}$

$R_{localizer}$

$R_{img\_sensor1}$

$R_{img\_sensor2}$

$R_{patient}$

R_{robot}

Pre-operatively | Intra-operatively
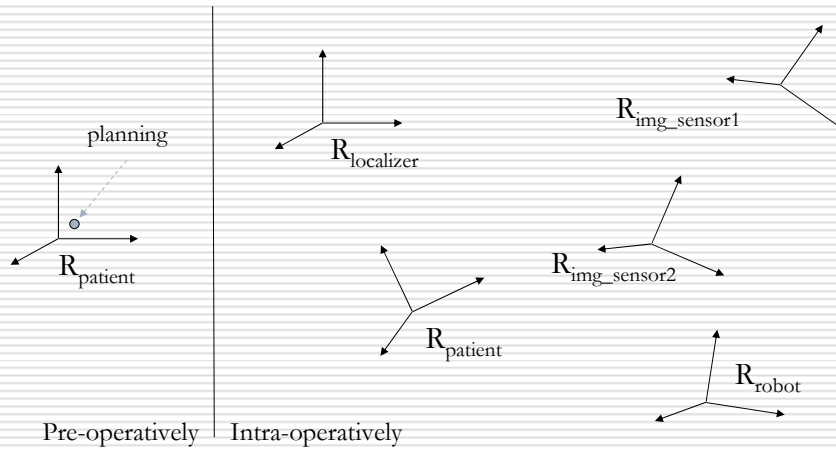
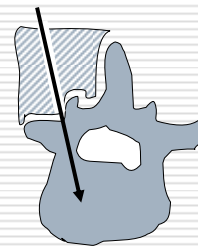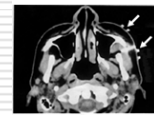Robot Registration – J. Troccaz

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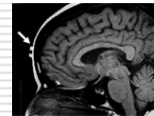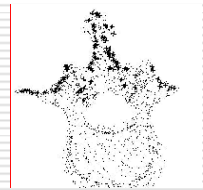# Registration basics

☐ Two reference frames R_A and R_B and a transform T_A^B to be determined

☐ Selection of features F_A in R_A and F_B in R_B

☐ Definition of a similarity measure (or distance) between F_A and F_B

☐ Determination of T_A^B such that the similarity is maximum (or distance minimum)

$$T_A^B = \arg\min d(F_A, T_A^B(F_B))$$

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Typical 3D/3D rigid registration methods

- ☐ Point to point (Procrustes)
  - ■ External fiducials
  - ■ Anatomical landmarks
- ☐ Surface registration
  - ■ Anatomical surface (i.e. ICP, chamfer matching)
  - ■ Template [Radermacher]
- ☐ Intensity-based registration (for images only)

Examples A

- ☐ Pre-op: planning on CT data
- ☐ Intra-op: a robot
- ☐ Developed methods:
  - ■ Robodoc: robot palpation of implanted fiducials
  - ■ ACRobot: robot palpation of anatomical surface
  - ■ CAD-Implant: fiducials+template (robot is pre-operative)

Robodoc (for hip surgery)

☐ Define precisely the prosthesis position (geometrical or biomechanical criteria)

☐ Improve the preparation of the hip cavity

Hip joint
Femur
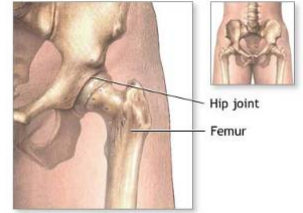
adam.com

A metal ball and stem are inserted in the femur and a plastic socket is placed in the enlarged pelvis cup

adam.com

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Robodoc [Taylor et al.]

2. *Pre-op to intra-op registration* using implanted titanium pins (anatomical registration in the last version)
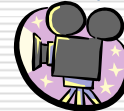
1. *Planning*: Orthodoc

6D force sensor

3. *Intra-operative bone milling* procedure using Robodoc (based on the IBM scara robot)

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Example A.1: Robodoc

3D/3D point-to-point registration

planning

$R_{patient}$

$R_{patient}$

Palpation

R_{robot}

Pre-operatively | Intra-operatively

ACRobot [Davies et al.]

- ☐ « Hands on » robot
- ☐ Knee arthroplasty
- ☐ 3 DOFs
- ☐ Bone surface palpated with the robot
- ☐ IEEE TRA 03: registration accuracy evaluation

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ACRobot registration tests

- ☐ Initial estimate from 4 anatomical landmarks
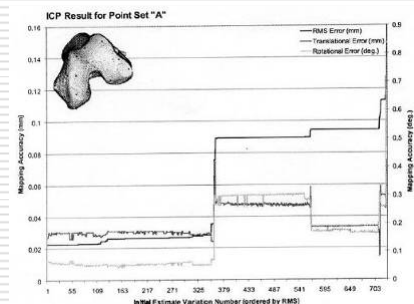- ☐ ICP surface matching
- ☐ Intra-op criterion: rms distance
- ☐ Does a small rms mean a good registration?
- ☐ Experiments with phantom and artificial data:
  - ■ Generated palpated points (10 to 100) with or without random noise added (max up to 1.5mm)
  - ■ Initial estimates in the range of +/-10mm and 2°
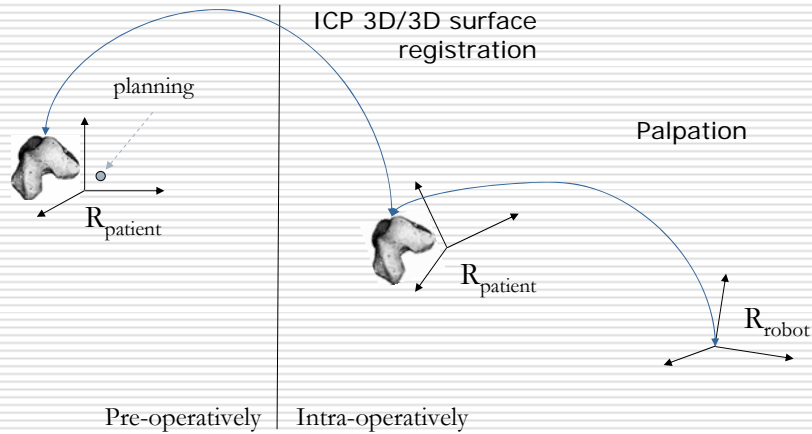 - ■ Known translational and rotational errors

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ACRobot: results

- ☐ Nb pts <70 makes ICP more problematic
- ☐ Results highly depend on the data sets
- ☐ May have a rms=0.6 with errors of 0.8mm and 2°

From [IEEE-TRA03]

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Example A.2: ACRobot

ICP 3D/3D surface registration

planning

$R_{patient}$

Palpation

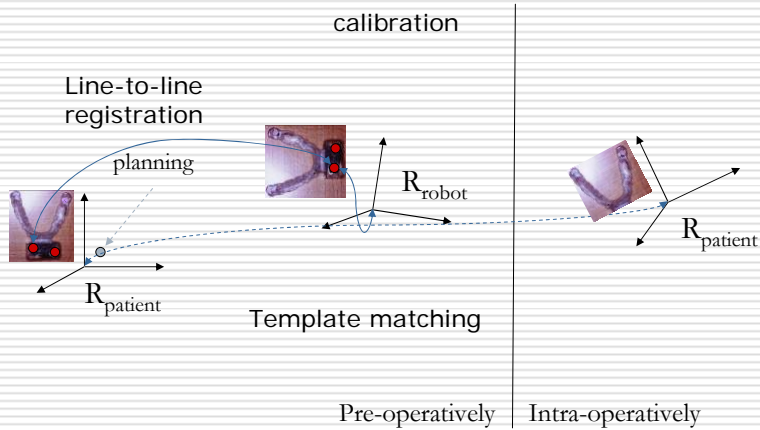$R_{patient}$

R_{robot}

Pre-operatively | Intra-operatively

CAD-Implant [Champleboux et al.]

☐ A system for dental implant assistance
☐ A template associated to fiducials visible on CT
☐ A pre-operative robot
☐ Intra-operatively: no robot, no computers
☐ Surface registration without computers

Example A.3: CAD-Implant

calibration

Line-to-line registration

planning

R_{robot}

$R_{patient}$

$R_{patient}$

Template matching

Pre-operatively | Intra-operatively
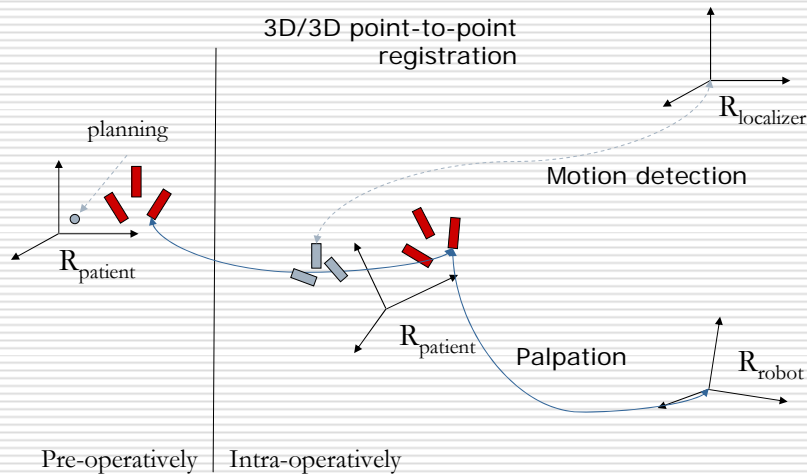
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Example B

- ☐ Close to Robodoc
- ☐ Knee application
- ☐ Pre-op: planning on CT data
- ☐ Intra-op: a robot, a tracking sensor
- ☐ Developed method:
  - ■ implanted fiducials S for registration
  - ■ fiducials S' for motion detection

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Example B: CASPAR

3D/3D point-to-point registration

$R_{localizer}$

Motion detection

planning

$R_{patient}$

$R_{patient}$

Palpation

R_{robot}

Pre-operatively | Intra-operatively

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Examples C

- ☐ Pre-op: planning on CT data
- ☐ Intra-op: a robot, X-Ray sensors
- ☐ Developed methods:
  - ■ Speedy V1 [Lavallée89]: Direct X-ray/robot calibration and manual image registration
  - ■ Cyberknife V1 [Schweikard98]: Indirect X-ray/robot calibration and intensity-based registration
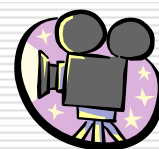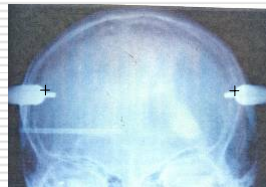
Speedy V1

- □ Stereotactic neurosurgery
- □ Pre-operative MR or CT
- □ Intra-operative X-Ray (AP and lateral) – several exams
- □ Direct X-Ray/robot calibration
- □ Manual image registration (anatomical for pre-op/intra-op and markers for intra-op/intra-op)
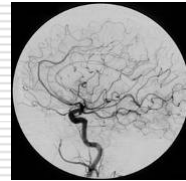
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Speedy

- □ X-Ray extrinsic calibration: bi-plane model

- □ 2D/2D image registration fiducials
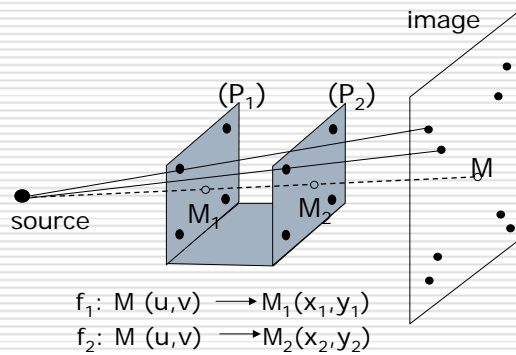
image

(P_1) (P_2)

M

source M_1 M_2

$f_1: M(u,v) \longrightarrow M_1(x_1, y_1)$
$f_2: M(u,v) \longrightarrow M_2(x_2, y_2)$

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Example C.1: Speedy V1

Pre-operatively | Intra-operatively

planning

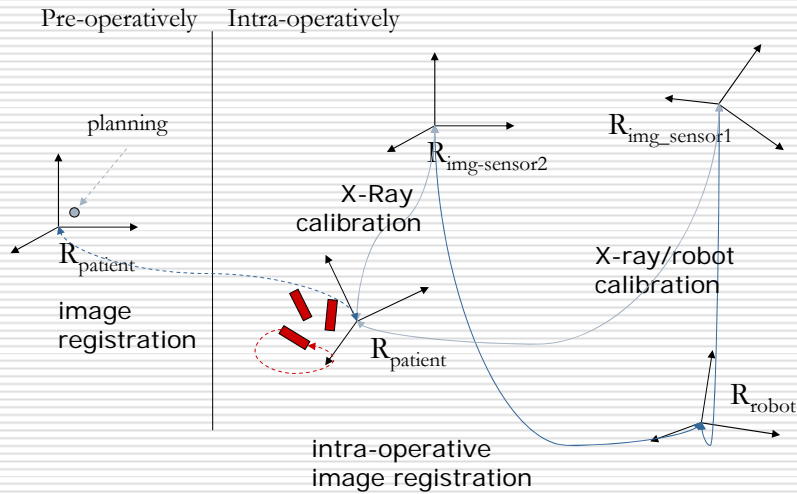$R_{img\text{-}sensor2}$

$R_{img\_sensor1}$

X-Ray calibration

$R_{patient}$

X-ray/robot calibration

image registration

$R_{patient}$

R_{robot}

intra-operative image registration
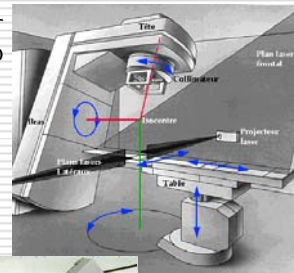

Cyberknife V1 [Schweikard et al.]

- ☐ Radiotherapy application
- ☐ Complex trajectories for improved tumor destruction (multiple radiation ports)
- ☐ 6 DOFs required
- ☐ Very heavy tools
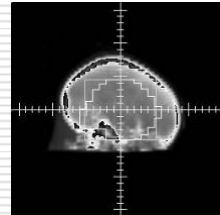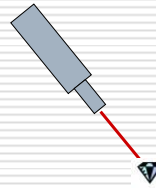
Traditional linear accelerator set-up

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

Cyberknife V1

□ Planning on CT data
□ Intra-operatively:
- Indirect X-Ray/robot calibration (via isocenter)
- « X-Ray/pre-computed DRRs » intensity-based registration (before each beam activation)
- Small motion compensation when necessary / interruption of the procedure and replanning for large motion

A Digitally Reconstructed Radiograph (DRR)

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Example C.2: Cyberknife V1

Pre-operatively | Intra-operatively

planning

$R_{img-sensor2}$

$R_{img\_sensor1}$

X-Ray calibration

X-Ray/Iso calibration

$R_{patient}$

iterated image registration

$R_{patient}$

Set-up

R_{robot}

$R_{isocenter}$

Robot/Iso calibration

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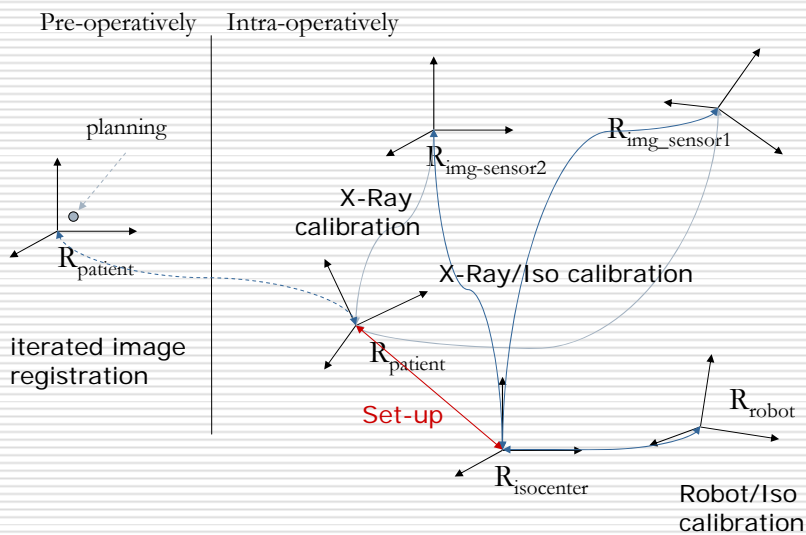
Example D: Cyberknife+synchrony

- 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
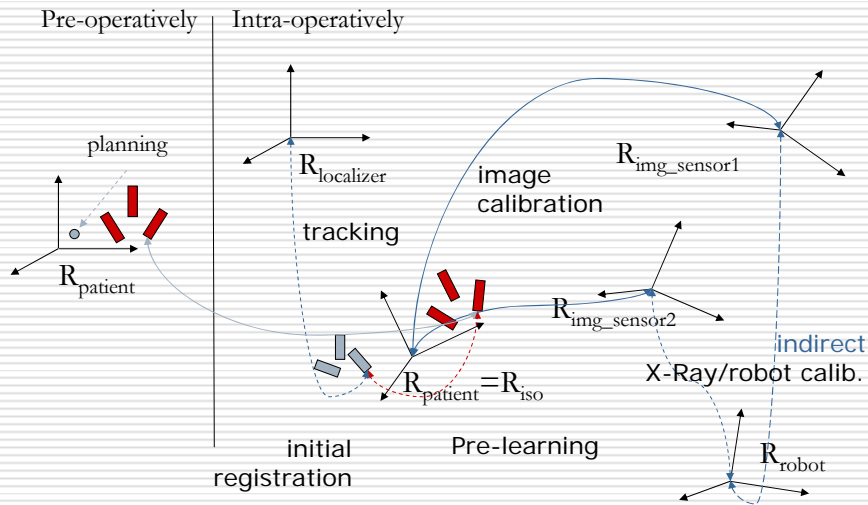

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Real-time registration

- Large motion tracking [Schweikard05]
  - Internal fiducials (gold seeds) for initial registration
  - External fiducials (IR diodes) for respiration tracking
  - Learning internal/external fiducials relationship

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Example D: Cyberknife+Synchrony

Pre-operatively | Intra-operatively

planning

$R_{localizer}$

image calibration

tracking

$R_{img\_sensor1}$

$R_{img\_sensor2}$

$R_{patient}$

$R_{patient} = R_{iso}$

indirect
X-Ray/robot calib.

R_{robot}

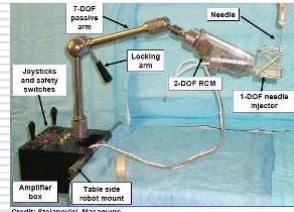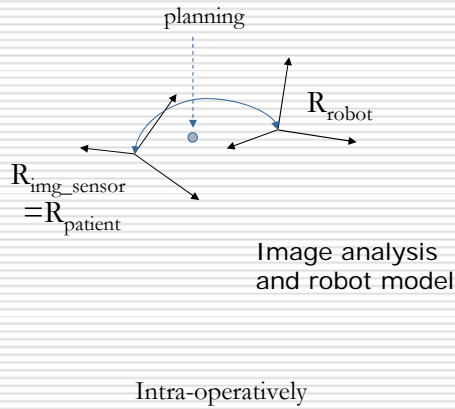initial registration

Pre-learning

Another type of solution (E)

☐ Target defined in the intra-operative imaging data*

☐ Examples

- ■ Indirect visual servoing: computing the robot position from the images
  - ☐ PAKY+RCM [Stoianovici et al.], LPR [Cinquin et al.], etc.
- ■ Direct visual servoing: modeling variations of the robot position to variations of the target in the images
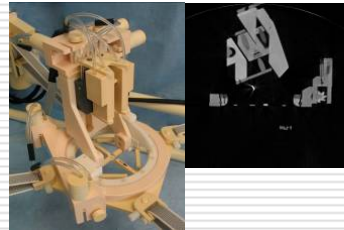 - ☐ GABIE [Morel], ZEUS [deMathelin], etc.

*if pre-operative planning: need for pre-op/intra-op registration

Summer School on Surgical Robotics — Montpellier, Sept. 09

Example E.1

planning

R_{robot}

$R_{img\_sensor} = R_{patient}$

PAKY+RCM

Image analysis and robot model

Intra-operatively

LPR

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Example E.2

planning

R_{robot}

$R_{img\_sensor} = R_{patient}$

tool — heart

P_1 — T_1

P_2 — T_2

US plane
$(\dot{\omega}_1, \dot{\omega}_2, \dot{\omega}_3, \dot{d}) = f(d(T_1, P_1),\ d(T_2, P_2))$

GABIE

Image analysis and Image/robot differential model

Intra-operatively

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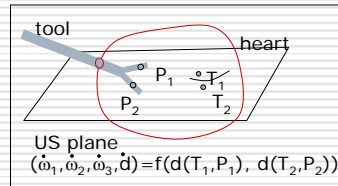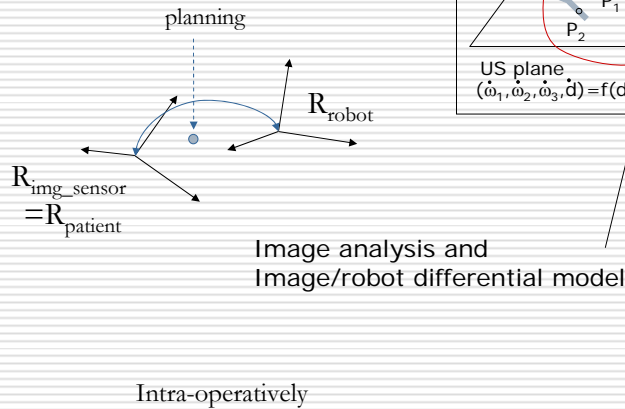
Discussion

- ☐ Modus operandi: many solutions
  - ■ Palpation (fiducial, anatomy): easy, invasive
  - ■ Imaging (anatomy): more difficult, less or non invasive
  - ■ Template: easy, limited to few applications
  - ■ Need for updated or real-time registration?
    - ☐ No motion
    - ☐ Motion detection
    - ☐ Discrete motion detection and compensation
    - ☐ Continuous motion detection and tracking

Discussion (cont'd)

- ☐ No universal recipies: depends on the application
- ☐ Some important issues
  - ■ Intra-operative evaluation of registration accuracy
  - ■ Safety of real-time registration