*Università di Roma "La Sapienza"*

# Medical Robotics

# Robot Registration

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it's in general the problem of determine geometric relationship between 2 reference frames

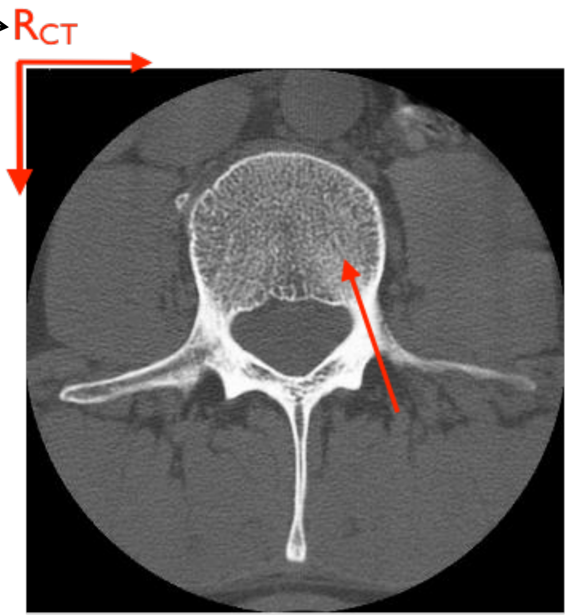
- registration: determine geometric relationships between two reference frames

we use this to find the geometric relation

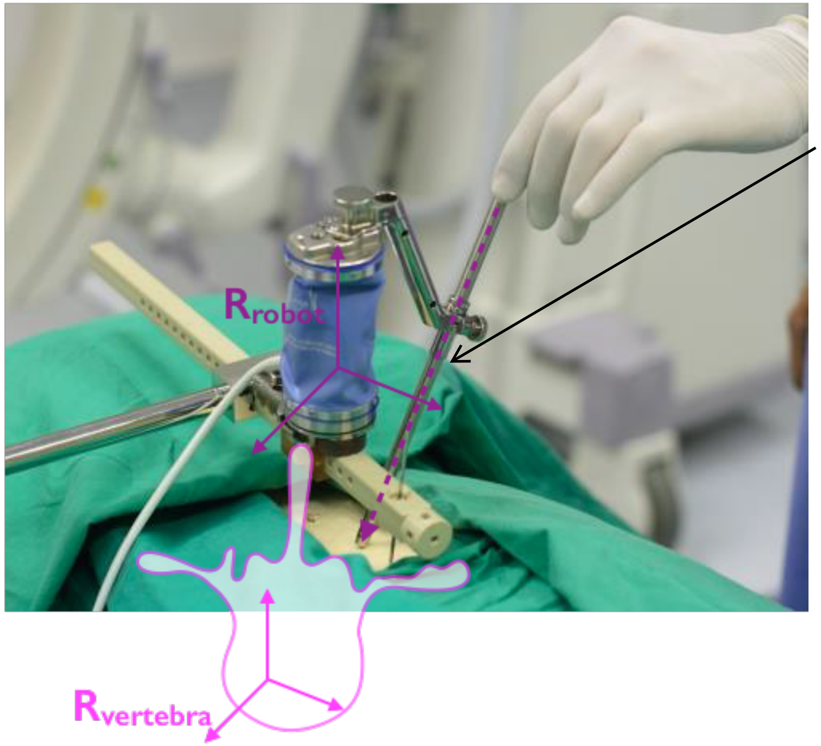
- robot registration: determine geometric relationships between reference frames allowing the transfer of surgical plans to the coordinate system of the robot

CT scan of the patient.

reference frame




the robot, along this direction, should drill and insert screw




Reinassance robot. It moves this guide in the desired direction of the screw insertion

the robot need to know this direction in its the reference frame, so the problem is how to allign this reference frame to the CT reference frame. So we need also to nkow where the vertebra is with respect to the robot.

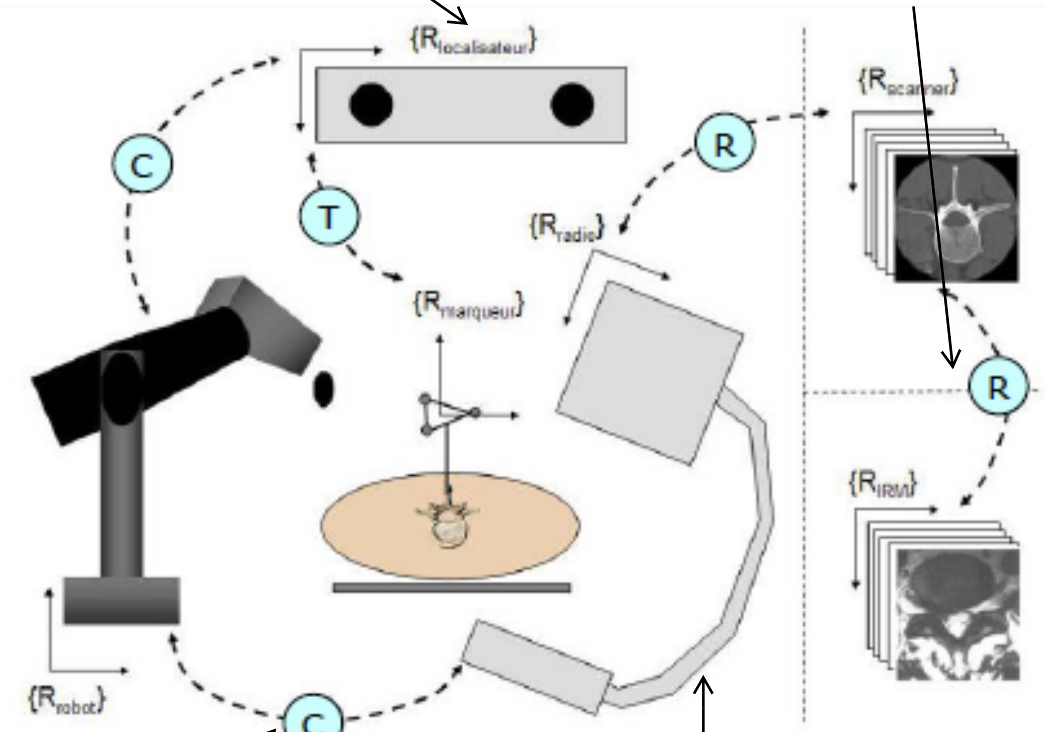
pre-operative

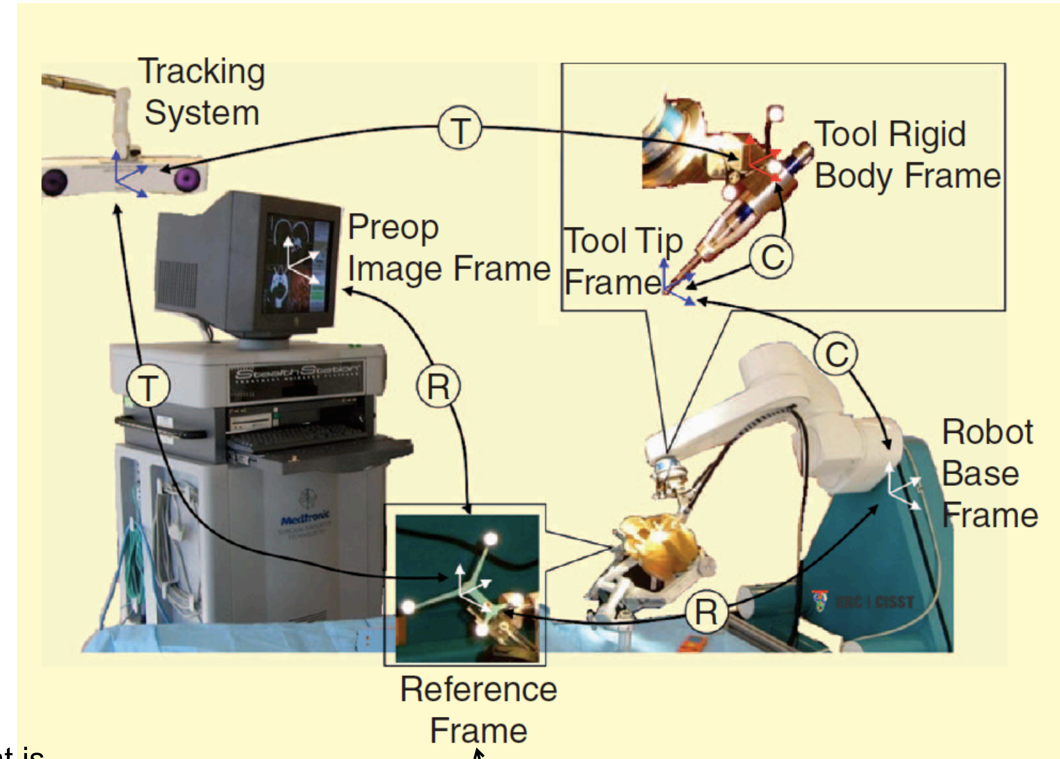
intra-operative

## in general, more reference frames might be involved

in the surgery room there is always a localizer, for ex.
an optical localizer, and the calibration is based on it

here we need registration
of the 2 reference frames




the relation between
these 2 is obtained
through calibration

this is a CT arm and it is used fluoroscopy that is
a form of realtime CT imaging during the surgery

that is visible to the localizer

tools calibration (C), tracking (T), registration data (R)

using patients data and external objects

requires intrinsic robot calibration!

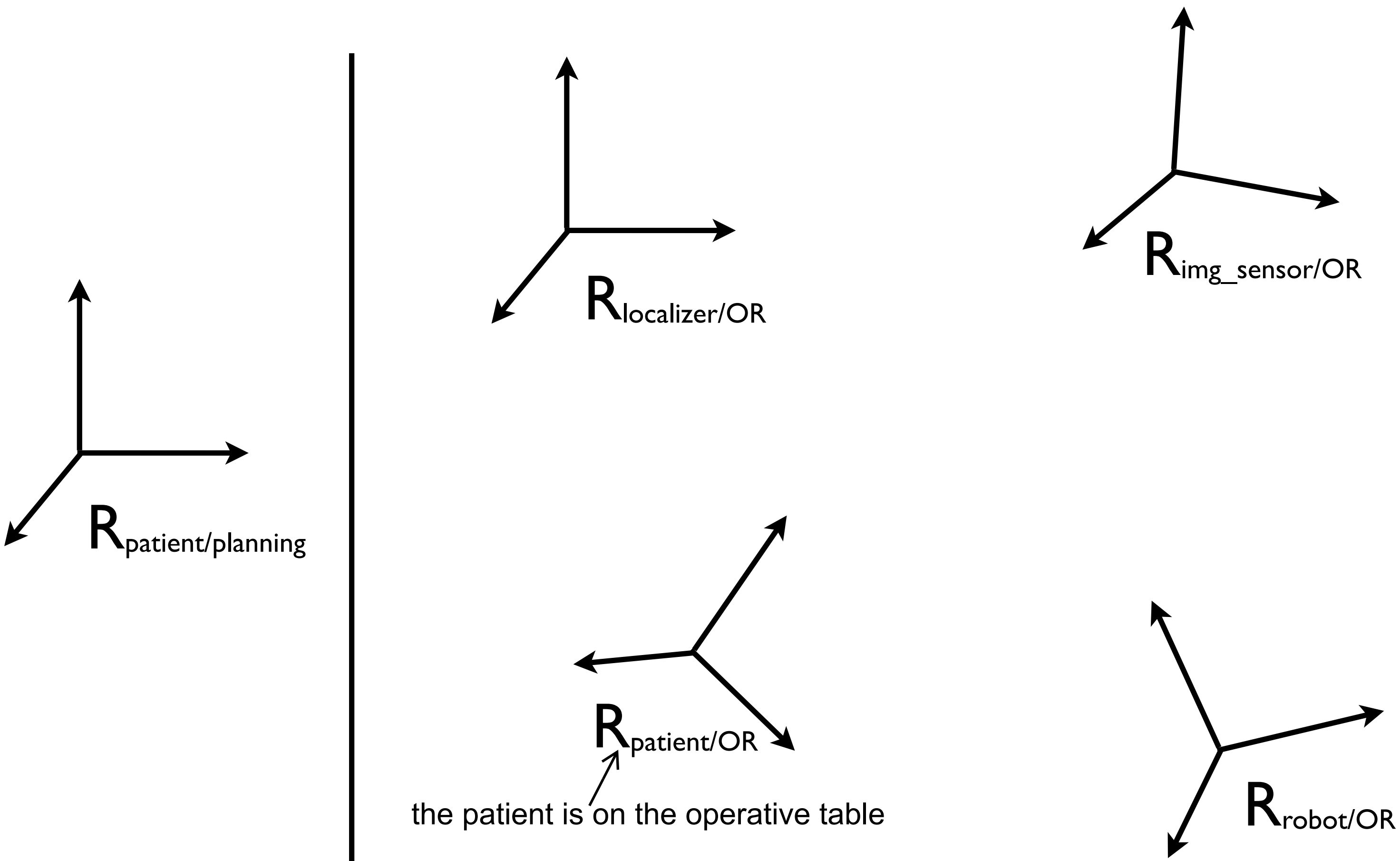
## devices

- localizers
  - most use  most used for research topic
  - optical (standard of care), magnetic (research topic), mechanical (early systems)


- imaging sensors (real-time modalities) used in clinical practices
  - fluoroscopy, ultrasound, digital x-ray

# possible reference frames of interest

we need to find the rototranslation matrices that allow to move between reference frames




**pre-operative data**

**intra-operative data**

we assume that there is a robot, but the registration process not necessarly implied the presence of robot

## registration basics

we want to determine

- given two reference frames $R_A$ and $R_B$, determine the transformation ${}^A\mathbf{T}_B$ (i.e., rotation ${}^A\mathbf{R}_B$ and translation ${}^A\mathbf{p}_{AB}$)

- select the feature ${}^A\mathbf{F}$ in $R_A$ and ${}^B\mathbf{F}$ in $R_B$

- define a similarity (or distance) measure between ${}^A\mathbf{F}$ and ${}^B\mathbf{F}$

- determine ${}^A\mathbf{T}_B$ maximizing similarity (minimizing the distance $d$)

optimization process=minimizing this function

$$ {}^A\mathbf{T}_B = \arg\min d({}^A\mathbf{F}, {}^A\mathbf{T}_B({}^B\mathbf{F})) $$

## rigid registration (case of a single point feature)

- given the coordinates ${}^A\mathbf{F} = [x_A, y_A, z_A]$ in $R_A$ and ${}^B\mathbf{F} = [x_B, y_B, z_B]$ in $R_B$

- determine ${}^A\mathbf{R}_B$ and ${}^A\mathbf{p}_{AB}$ s.t.

$$ {}^A\mathbf{F} = {}^A\mathbf{R}_B\, {}^B\mathbf{F} + {}^A\mathbf{p}_{AB} $$

# 3D/3D rigid registration methods

- point-to-point: one to one matching between a set of $N$ points ($N \geq 3$) in a coordinate frame and the corresponding $N$ points in another coordinate frame (Procrustes* problem); solved with standard point matching methods, can be used with
  - external fiducial
  - anatomical landmarks
- point-to-surface: correspondences between a set of points gathered intraoperatively and a 3D model of the surface reconstructed from preoperative images;
  - can be applied to surface-to-surface registration by sampling one of the two surfaces
  - mainly solved with the Iterative Closest Point (ICP) algorithm

*An ancient Greece smith (and robber) who used to physically attack people by stretching them or cutting off their legs, so as to force them to fit the size of an iron bed.

# orthopedics

the virtual fixture or operative control are based on a plan determined in the preoperative phase and in this case the movements are constrained

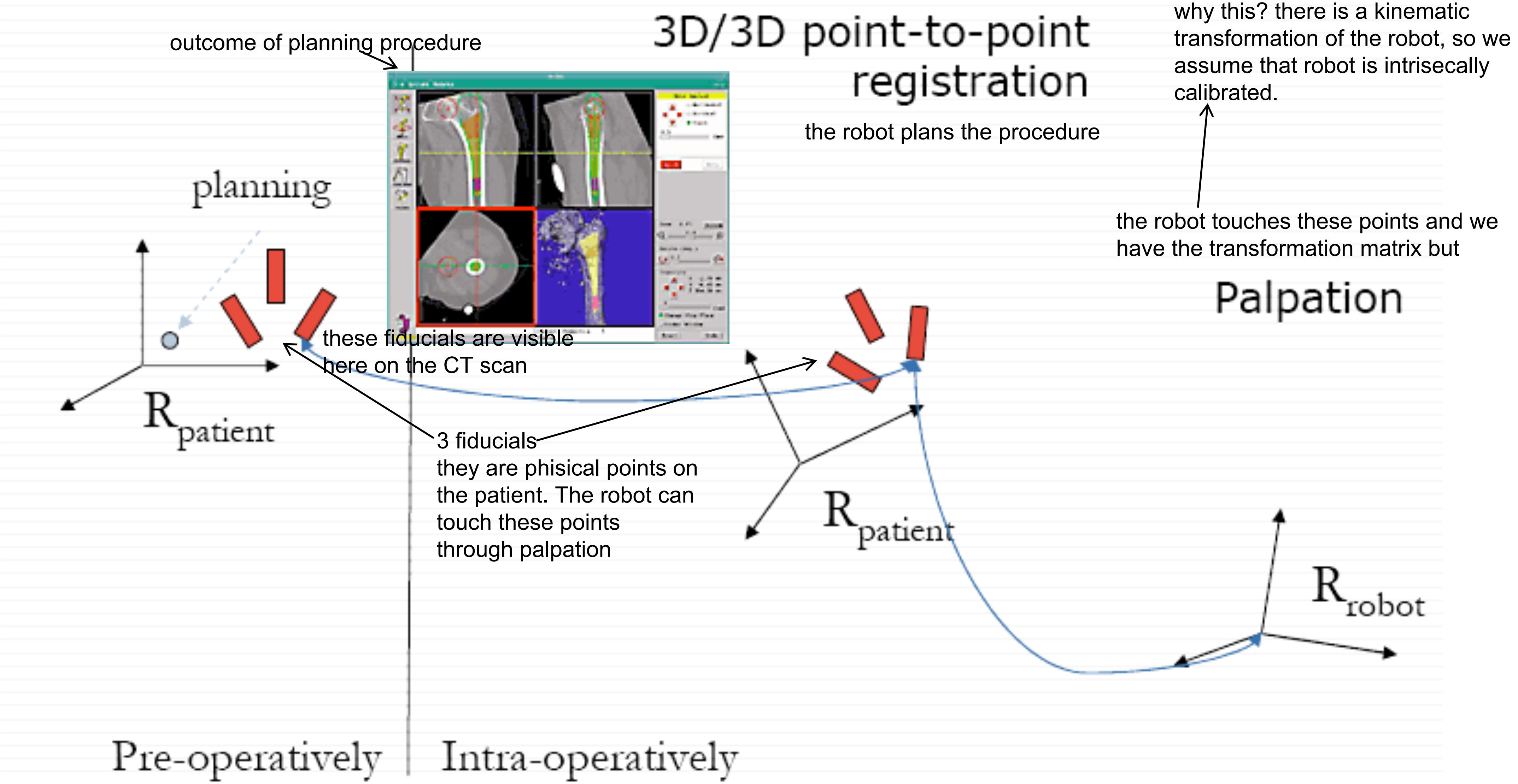
- pre-op phase: planning on CT data

- intra-op phase: surgery executed by the robot

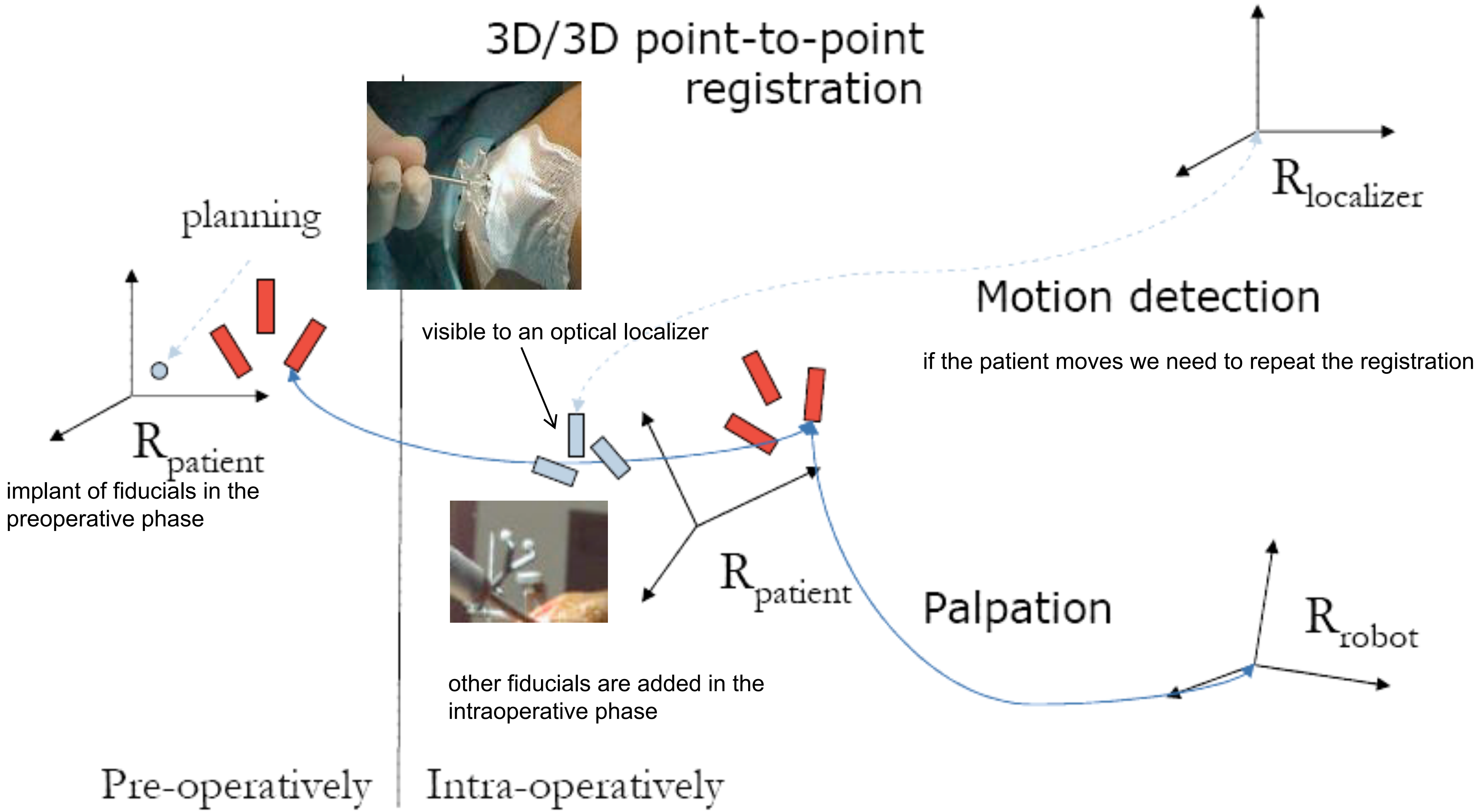
- examples of registration methods
  - Robodoc: palpation of implanted fiducials executed by the robot
  - Caspar: palpation of implanted fiducials + tracking for motion detection
  - Acrobot: palpation of anatomical surfaces

## examples (1): Robodoc (hip surgery)

the robot works in its reference frame so any task to be executed must be in its reference frame



## examples (2): CASPAR (knee surgery)



- similar to Robodoc

- pre-op phase: planning on CT data

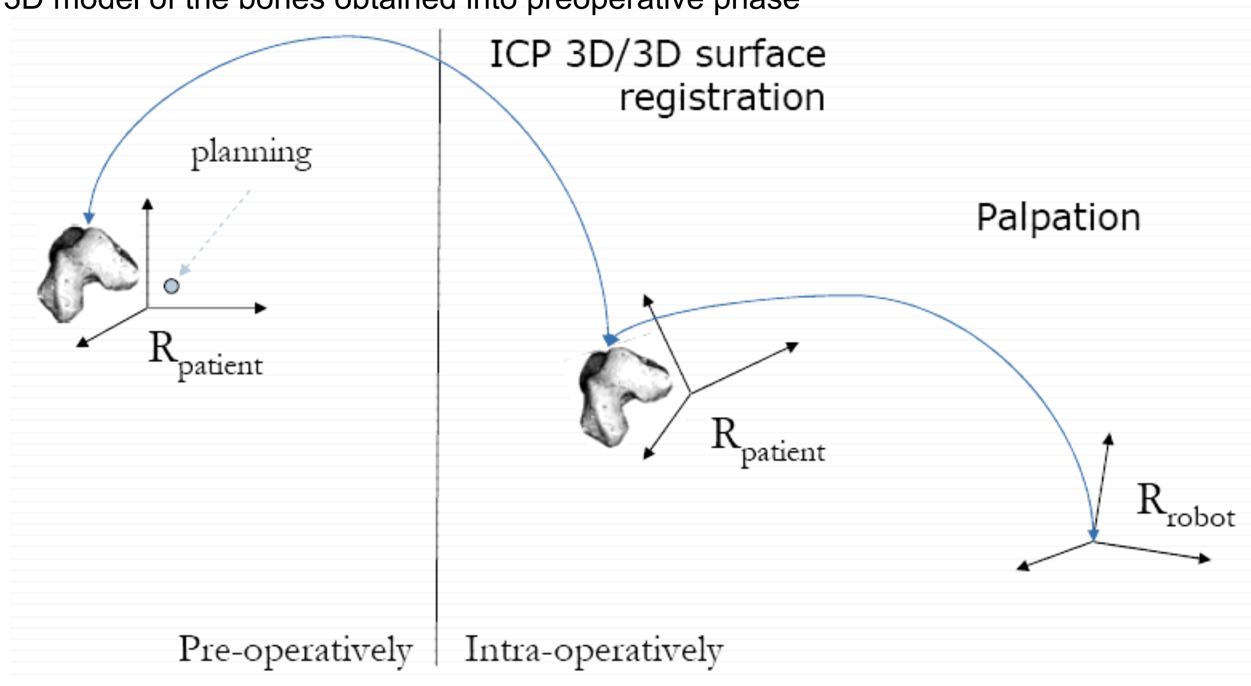
- intra-op phase: a robot and a sensor for patient tracking
  - fiducials S for registration
  - fiducials S′ for motion detection

hands-on control modality

here there is a non invasive method for registration

# examples (3): Acrobot (knee surgery)

It uses a 3D model of the bones obtained into preoperative phase

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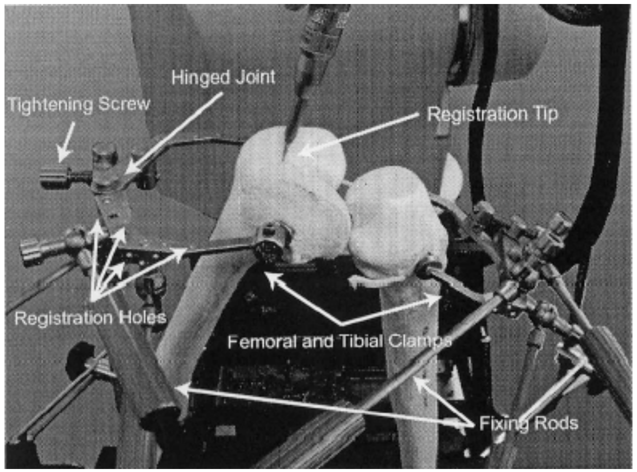
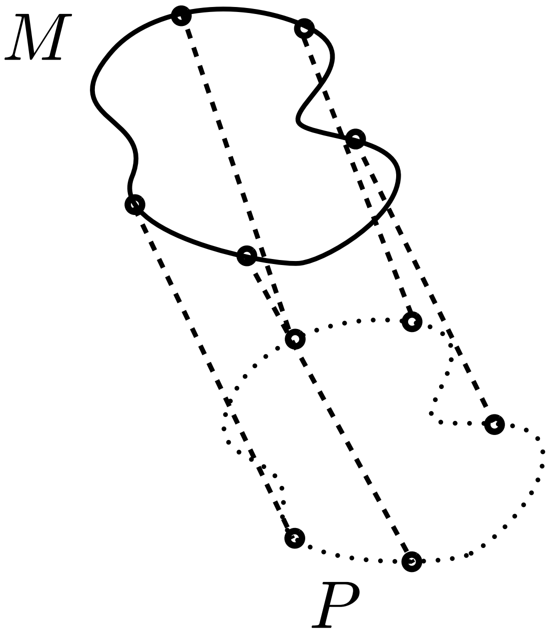
regions are computed and considered safe regions. When the surgeon moves thhe tools with the cooperation of the robot



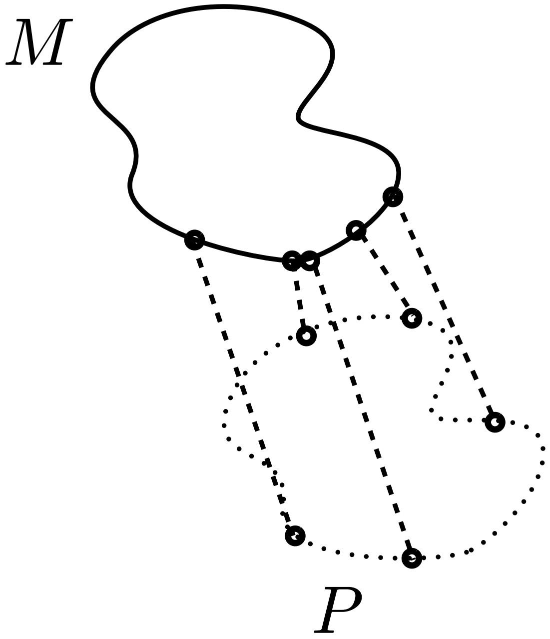

the patient is immobilized in a fixed position. In the preoperative phase the 3D model is reconstructed and in the intraoperative phase the surgeon will guide the robot (there is a surgical tool tip) in a way to touch it in a set of points in different locations. Using these point sampled in the intraoperative phase a registration procedure will be implemented based on ICP algo that will match these set of points on the 3D model

# Iterative Closest Point (ICP)

problem: given the point set $P$ with $N_p$ points from the *data shape* and the *model shape* $M$ with $N_m$ supporting points (or other geometric primitives) find the transformation that, when applied to $P$, provides the best alignment of the two point sets




known correspondence




unknown correspondence

idea: under certain conditions, the point correspondence provided by sets of closest points is a reasonable approximation to the true point correspondence point-to-surface registration (Acrobot) We always need 2 reference frames

1. initial estimate of the transformation ${}^AT_B^0$ allowing expression of the coordinates of the intra-op acquired points ${}^BF = \{{}^Bf_i\}$ $(i = 1, \ldots, N_p)$ in the frame $R_A$ of the model $M$ reconstructed from pre-op acquired data: ${}^A\tilde{F}_0 = {}^AT_B^0({}^BF)$ (with ${}^AF = \{{}^Af_i\}$)

   initial estimate of the transformation matrix

2. identification of the closest points on $M$: ${}^AF_0 = \text{closest}({}^A\tilde{F}_0, M)$ (correspondences)

   we denote with this, the points in M which are closest to this transformation Fzero tilde

   correspondence phase

3. application of a point-to-point registration method for a new estimate of the transformation
   ${}^AT_B^{k+1} = \text{arg min } d({}^AF_k, {}^AT_B^{k+1}({}^BF))$, $k = 0, \ldots$

4. terminate when the error is below a given threshold $\tau$

* the function to be minimized is $d({}^A\mathbf{F}, {}^AT_B({}^B\mathbf{F})) = \frac{1}{N}\sum_{i=1}^{N} ||{}^Af_i - {}^A\mathbf{R}_B\, {}^Bf_i - {}^A\mathbf{p}_{AB}||$, where points ${}^Af_i$ correspond to points ${}^Bf_i$ determined by the operator 'closest'

* the error at $k$-th step is $e_k = \frac{1}{N}\sum_{i=1}^{N} ||{}^Af_{ik} - {}^A\mathbf{R}_B^k\, {}^Bf_i - {}^A\mathbf{p}_{AB}^k||$

* other choices are possible

- the solution is guaranteed to converge to a *local* minimum
- algorithm sensitive to initialization

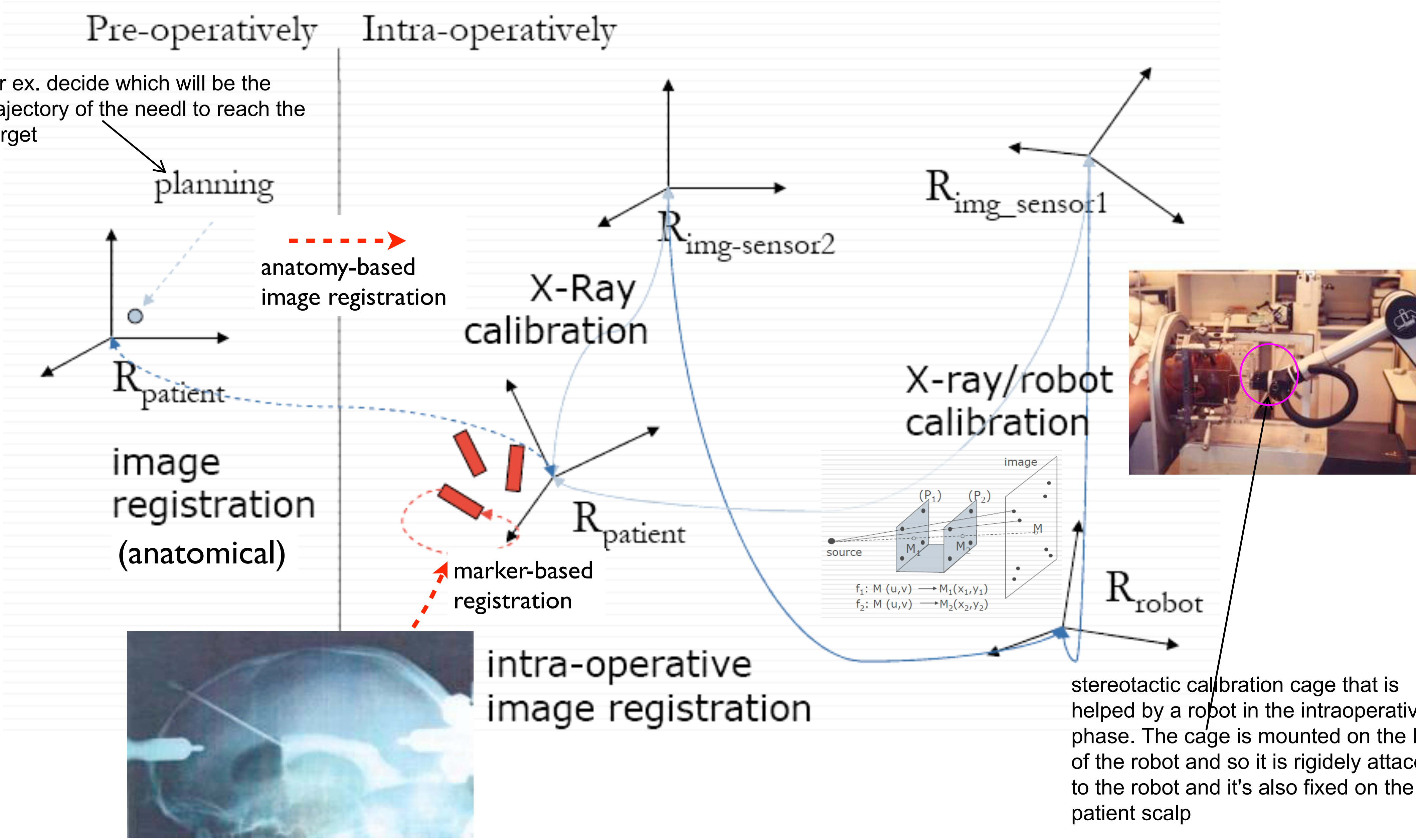
# Acrobot registration

- the surgeon acquires 4 points on the bone to initialize the ICP algorithm
- the surgeon acquires a set of randomly selected points (between 20 and 30) on the exposed surface of the bone
- the ICP algorithm determines the matching between this set of points and the model of the bone surface obtained in the pre-op phase through CT images
- the accuracy of the registration is validated through a software allowing to graphically display the position of the palpated points w.r.t. the bone surface
- if the registration is not accurate enough, the ICP procedure is repeated with a new set of points
- femoral and tibial clamps form a rigid body with the bone and present holes allowing easy re-registration in case of patient motion
- evaluation of the registration accuracy in [IEEE-TRA03]

## examples (4): Speedy (stereotactic neurosurgery)

used in neurosurgery

for ex. decide which will be the trajectory of the needl to reach the rarget



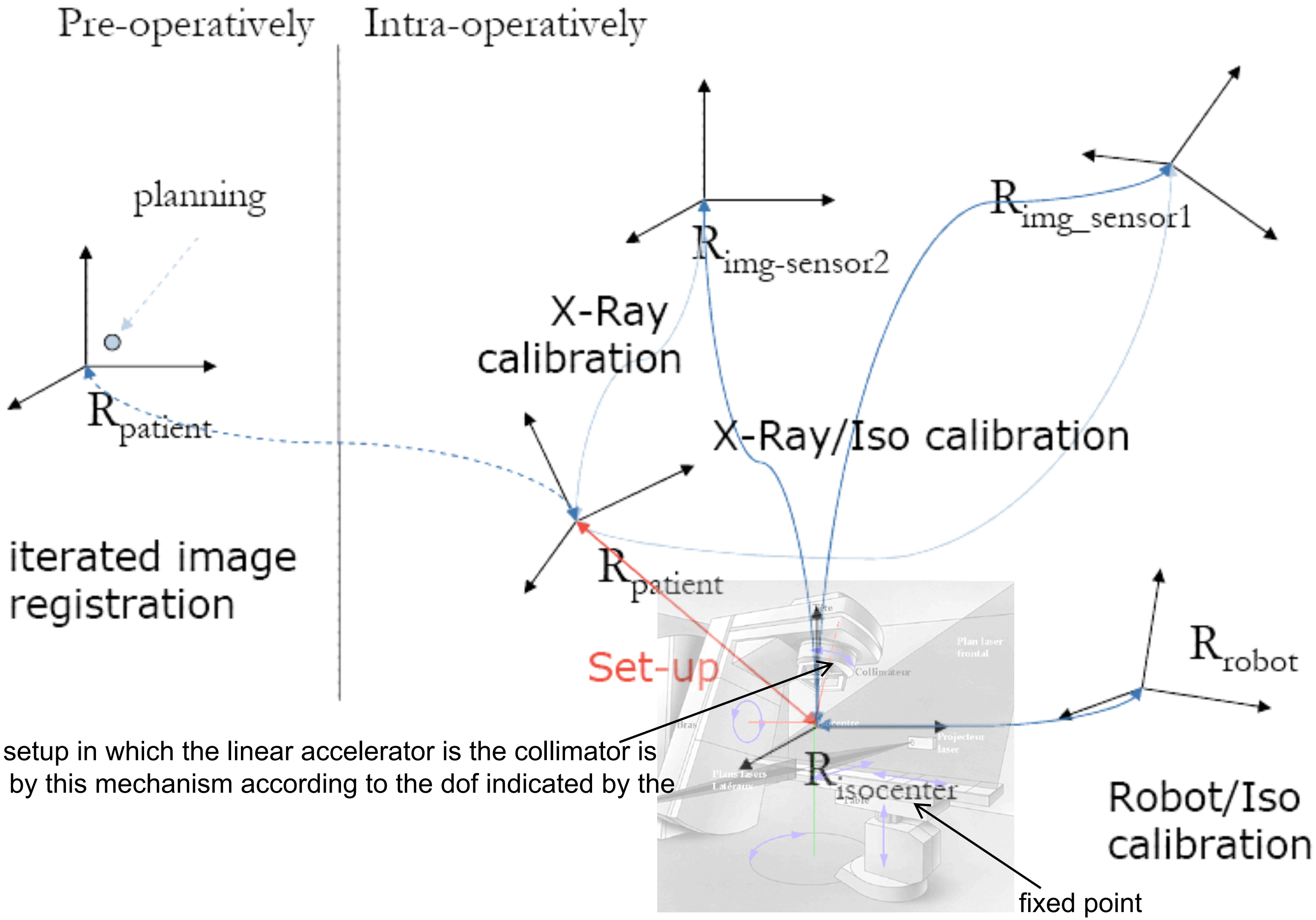

stereotactic calibration cage that is helped by a robot in the intraoperative phase. The cage is mounted on the E-E of the robot and so it is rigidely attacched to the robot and it's also fixed on the patient scalp

- pre-op: planning on CT data
- intra-op: a robot, x-ray sensors
  - Speedy [Lavallée]
    - pre-op: MR ot CT
    - intra-op: X-ray
    - direct calibration X-ray/robot with calibration cage
    - manual image registration (anatomical for preop/intra-op and markers for intra-op/intra-op)

# examples (5): Cyberknife (radiotherapy)

## isocentric beam generation mode

manual setup and then possibly reregistration using digitally reconstructed radiography



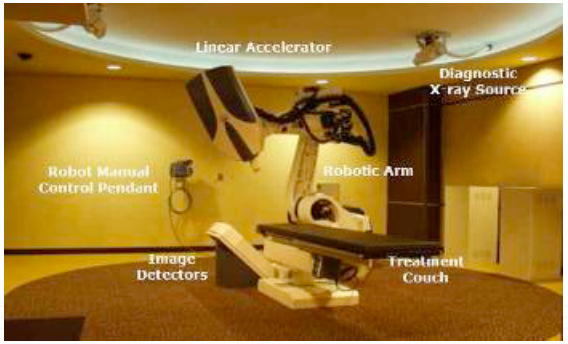

this is a traditional setup in which the linear accelerator is the collimator is here and is moved by this mechanism according to the dof indicated by the blue arrow

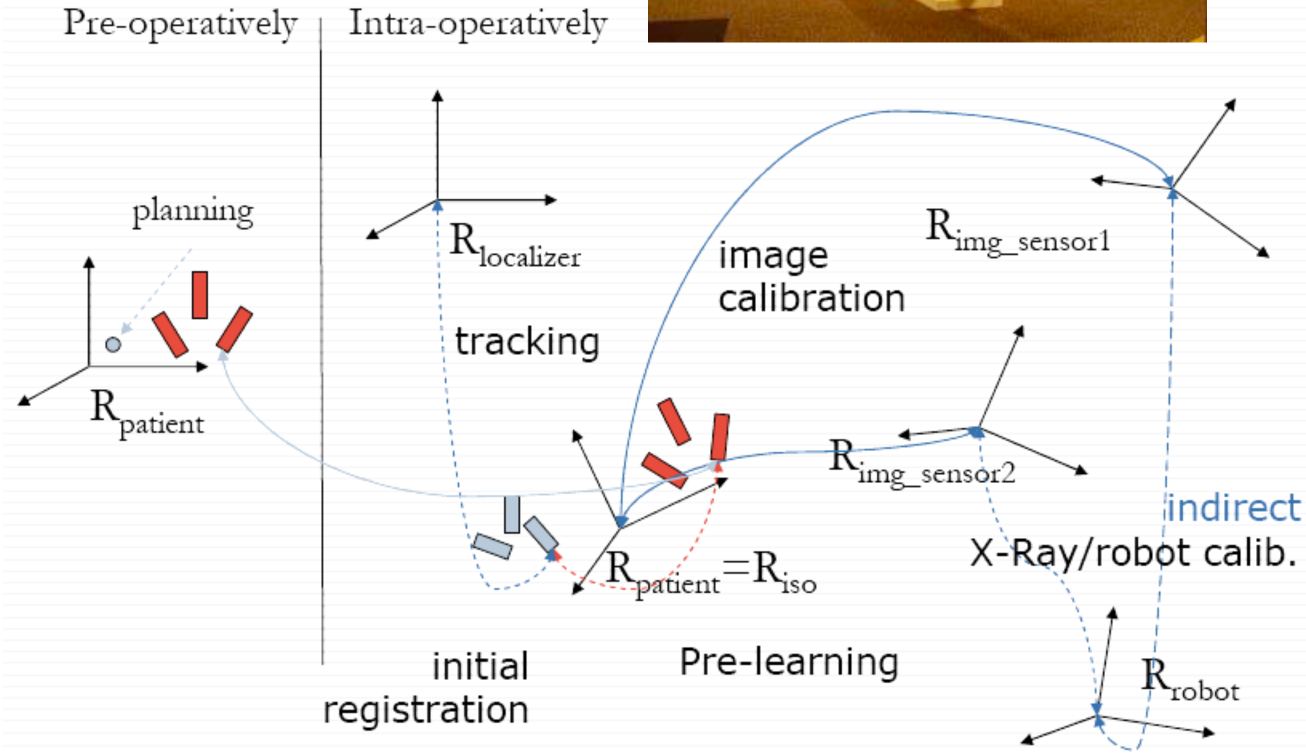
- pre-op: planning on CT data
- intra-op: a robot, x-ray sensors
  - Cyberknife [Schweikard]: indirect X-ray/robot calibration (via isocenter)
    - pre-op: planning on CT data
    - intra-op
      - indirect X-ray/robot calibration (via isocenter)
      - x-ray/DRR registration (Digitally Reconstructed Radiography): intensity-based registration before each beam activation
      - when necessary: interruption of the procedure and replanning for large motion

## examples (6): Cyberknife+Synchrony

VIDEO

**non-isocentric beam generation mode**

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- pre-op: planning on CT data
- intra-op: a robot, two x-ray sensors, one localizer
  - 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
- real-time registration for large motion tracking
  - internal fiducials (gold seeds) for initial registration
  - external fiducials (IR diodes) for respiration tracking
  - learning internal/external fiducials relationship

## Bibliography


- most of the lecture is taken from the slides by J. Troccaz
  http://www.lirmm.fr/ w3rob/UEE09/doc/Lecturers/Troccaz-Robot-registration.pdf

- M. Jakopec, F. Rodriguez y Baena, S. j. Harris, P. Gomes, J. Cobb, B. L. Davies, "The hands-on orthopaedic robot "Acrobot": Early clinical trials of total knee replacement surgery," IEEE Transactions on Robotics and Automation, Special Issue on Medical Robotics, vol. 19, no. 5, pp. 902–911, 2003.

- P. J. Besl, N. D. McKay, "A method for registration of 3-D shapes," IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 14, no. 2, pp. 239–256, 1992.

- S. Lavallée, J. Troccaz, L. Gaborit, P. Cinquin, A. L. Benabid, D. Hoffmann, "Image guided operating robot: a clinical application in stereotactic neurosurgery," 1992 IEEE International Conference on Robotics and Automation, Nice, France, 1992.

- A. Schweikard, G. Glosser, M. Bodduluri, M. Murphy, J. Adler, "Robotic motion compensation for respiratory motion during radiosurgery," Journal of Computer Aided Surgery, Special Issue on Planning and Image Guidance in Radiation Therapy, vol. 5, no. 4, pp. 263–277, 2000.

- W. Kilby, J. R. Dooley, G. Kuduvalli, S. Sayeh, C. R. Maurer, "The CyberKnife Robotic Radiosurgery System in 2010," Technology in Cancer Research and Treatment, vol.9, no. 5, pp. 433–452, 2010.