Università di Roma "La Sapienza"

Medical Robotics

Robot Registration

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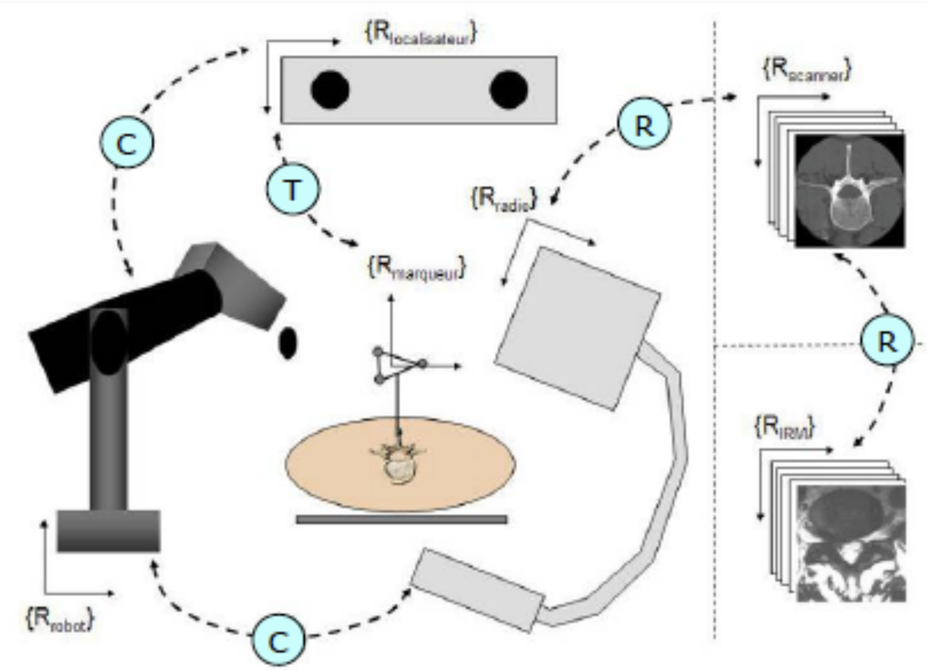
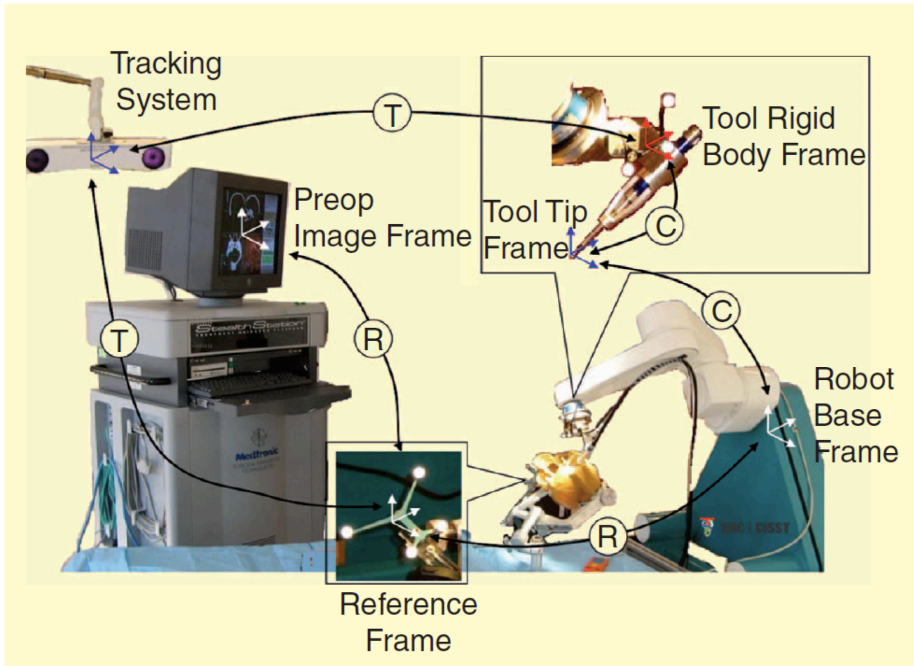
- registration consists in determining geometric relationships between two reference frames
- robotic registration essentially consists in transferring plans to the coordinate system of the robot



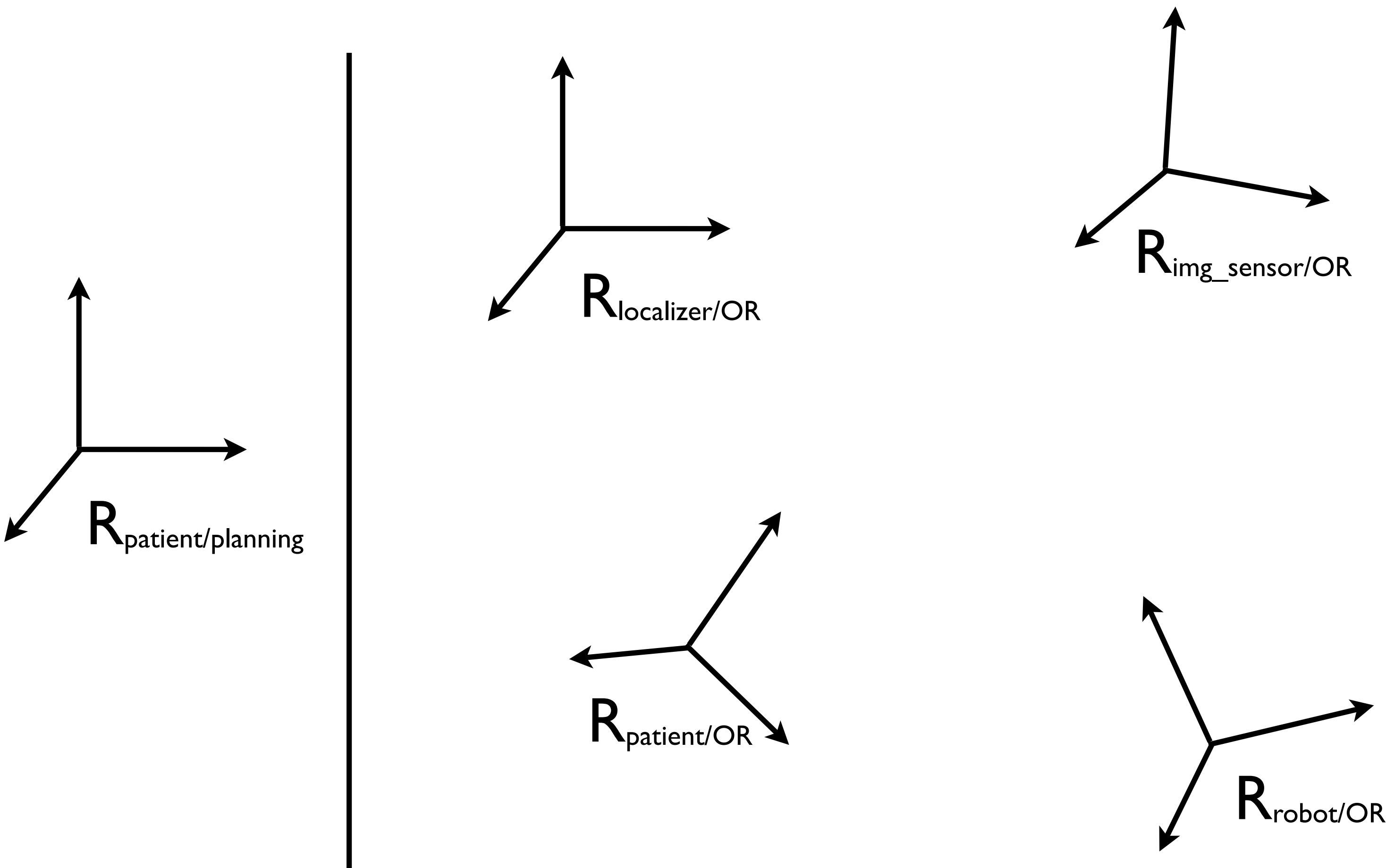


tools calibration, tracking, registration data

using patients data and external objects

requires intrinsic robot calibration!

possible reference frames of interest



pre-operative data

intra-operative data

tools

- localizers
  - optical (standard of care), magnetic (research topic), mechanical (early systems)

- imaging sensors
  - fluoroscopy, ultrasound, digital x-ray

registration basics

- 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)

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

rigid registration (case of a single 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 physically attacked people by stretching them or cutting off their legs, so as to force them to fit the size of an iron bed.

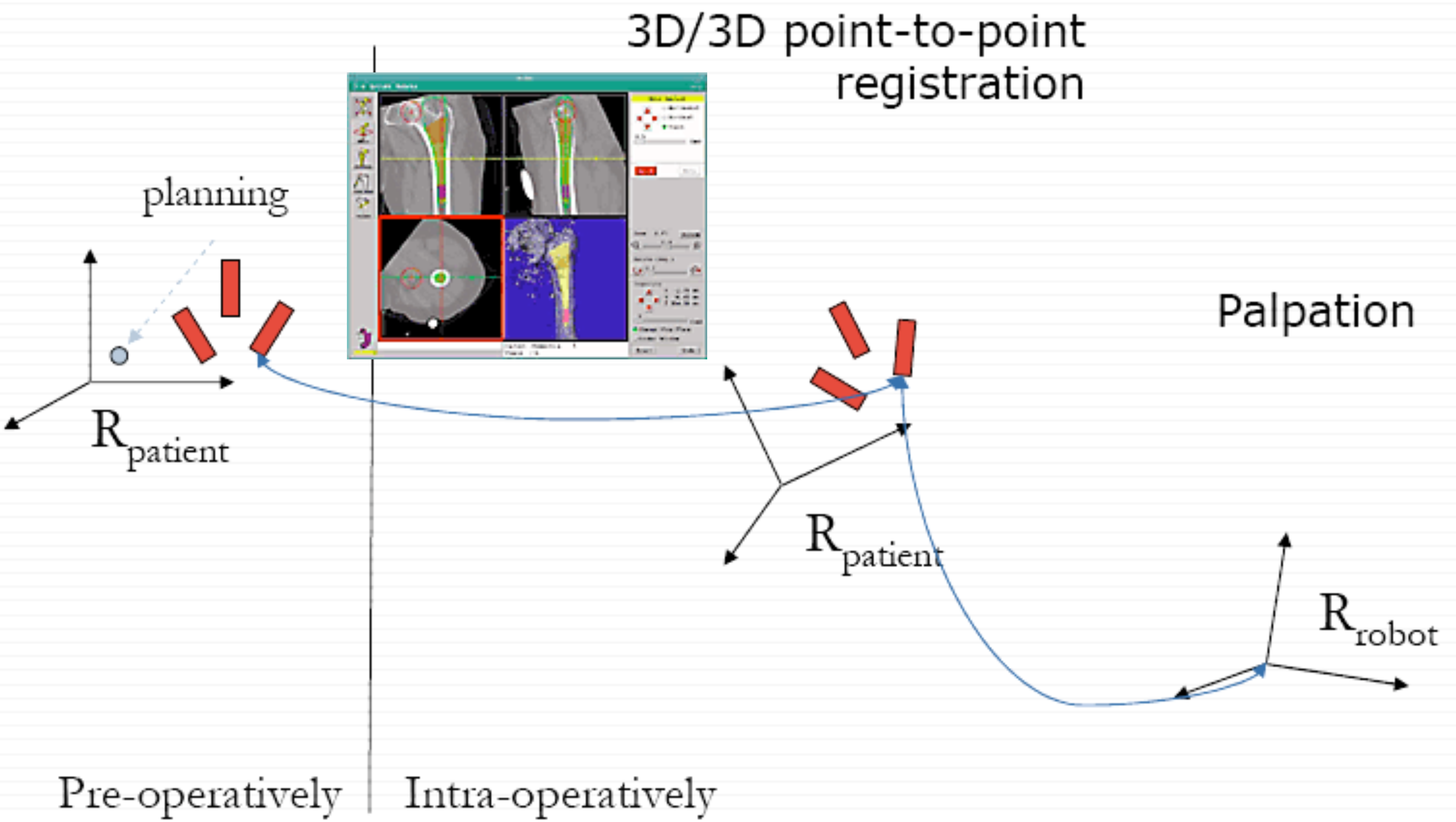
orthopedics

- pre-op phase: planning on CT data

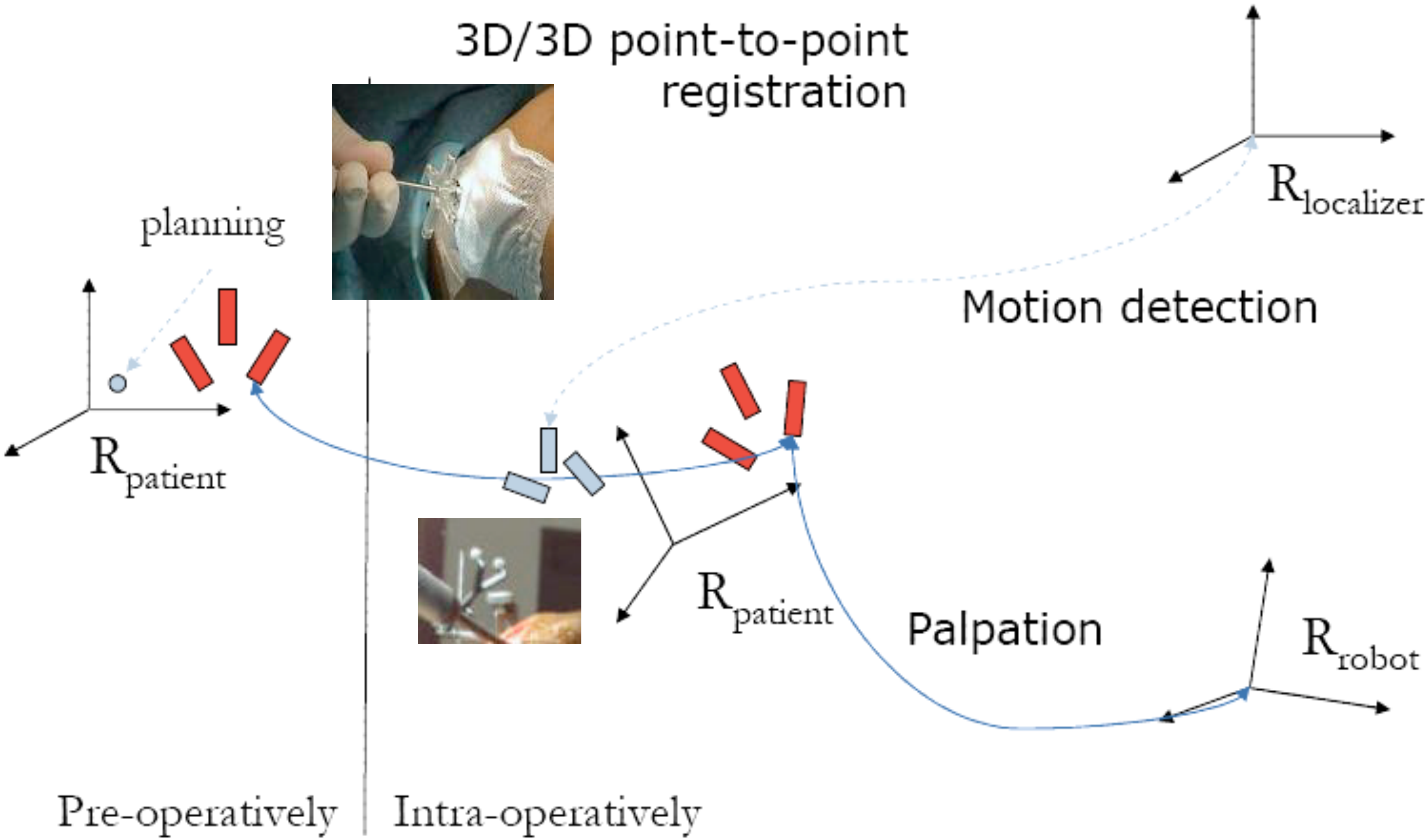
- intra-op phase: surgery executed by the robot

- methods used for the registration
  - 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)



examples (2): CASPAR (knee surgery)

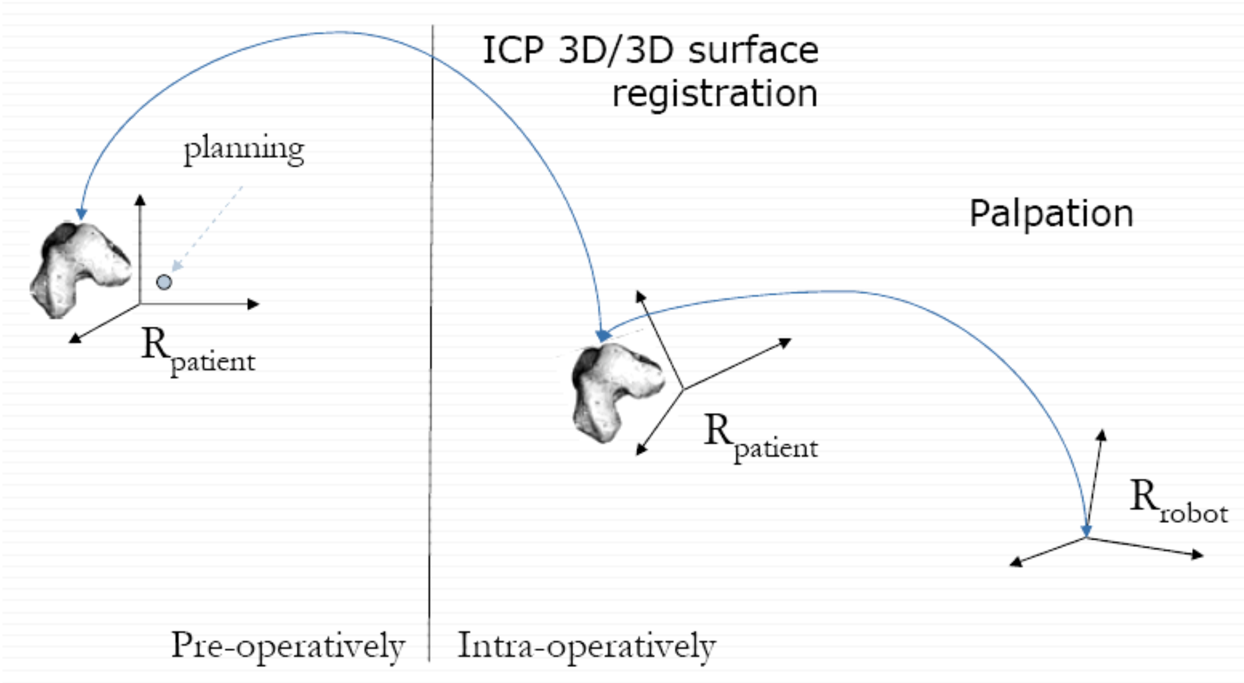


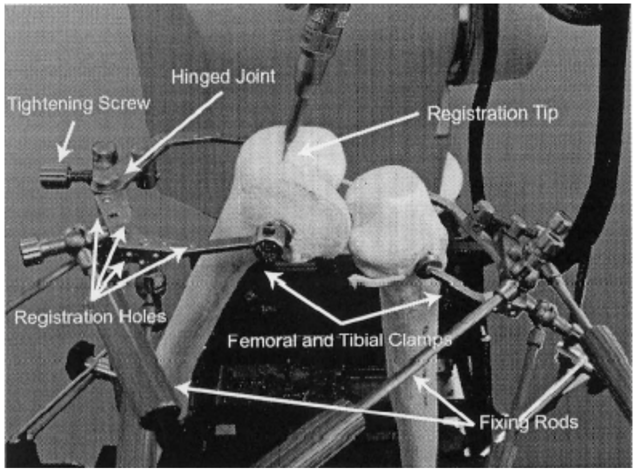
- similar to Robodoc

- 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

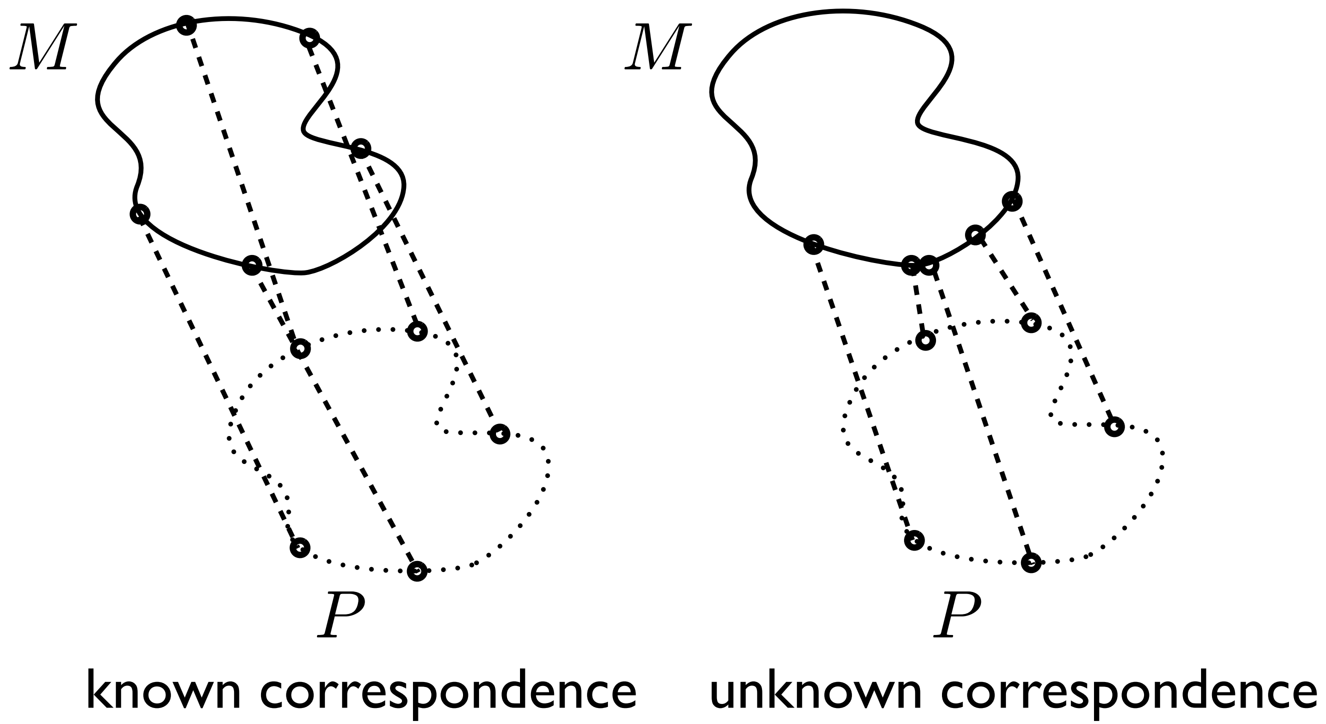
examples (3): Acrobot (knee surgery)





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



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)

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

2. identification of the closest points on M: ${}^{A}F_0 = \text{closest}({}^{A}\tilde{F}_0, M)$ (correspondences)

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

4. terminate when the error is below a given treshold τ

* the function to be minimized is $d({}^{A}\mathbf{F}, {}^{A}T_B({}^{B}\mathbf{F})) = \frac{1}{N}\sum_{i=1}^{N} ||{}^{A}f_i - {}^{A}\mathbf{R}_B\, {}^{B}f_i - {}^{A}\mathbf{p}_{AB}||$, where points ${}^{A}f_i$ corresponds to points ${}^{B}f_i$ (determined by the operator ‘closest’)
* the error at k-th step is $e_k = \frac{1}{N}\sum_{i=1}^{N} ||{}^{A}f_{ik} - {}^{A}\mathbf{R}_B^k\, {}^{B}f_i - {}^{A}\mathbf{p}_{AB}^k||$
* 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

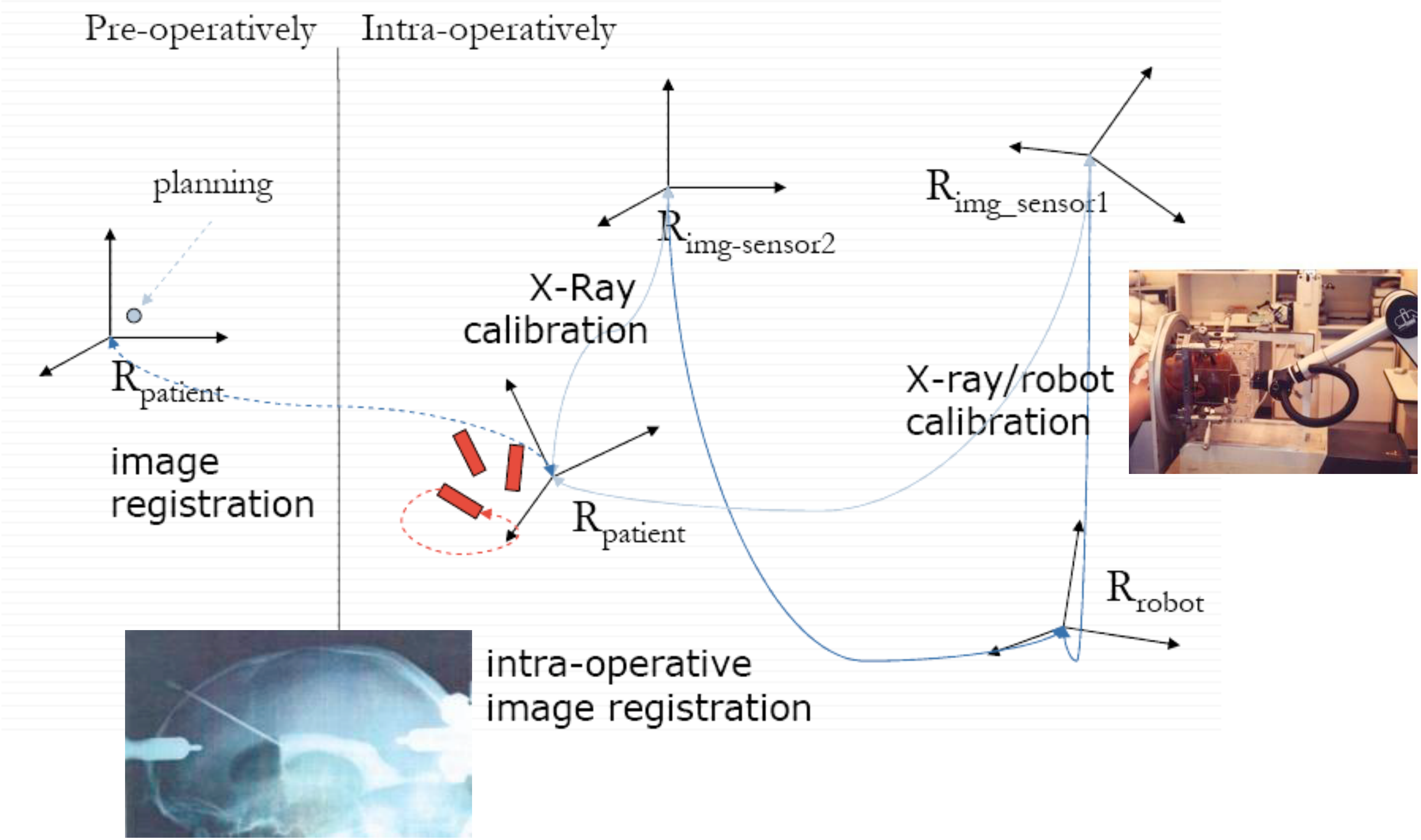
- the accuracy of the registration is validated through a software allowing to graphically display the position of the palpated points w.r.t. the bone surface

- 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]

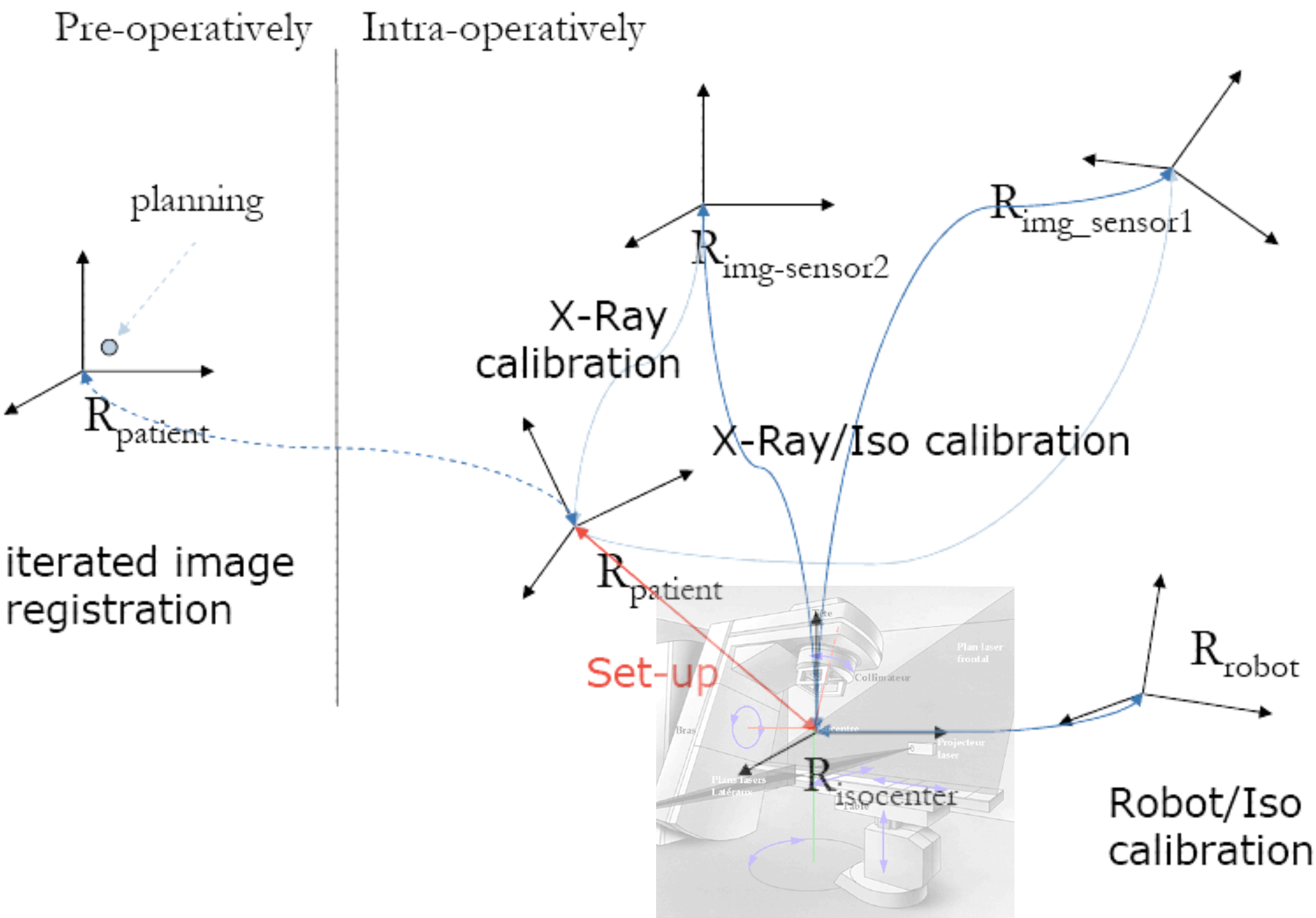
examples (4): Speedy (stereotactic neurosurgery)



- pre-op: planning on CT data
- intra-op: a robot, x-ray sensors
  - Speedy [Lavallée]
    - pre-op: MR o CT
    - intra-op: X-ray AP and lateral
    - 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)

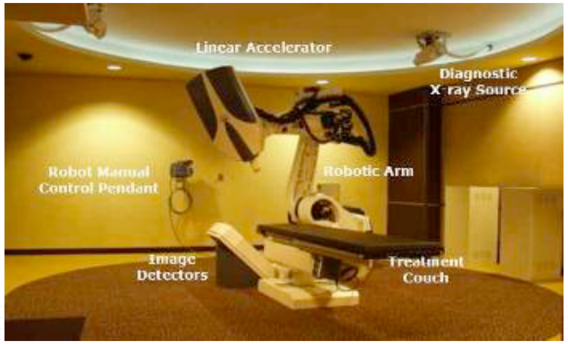
isocentric beam generation mode

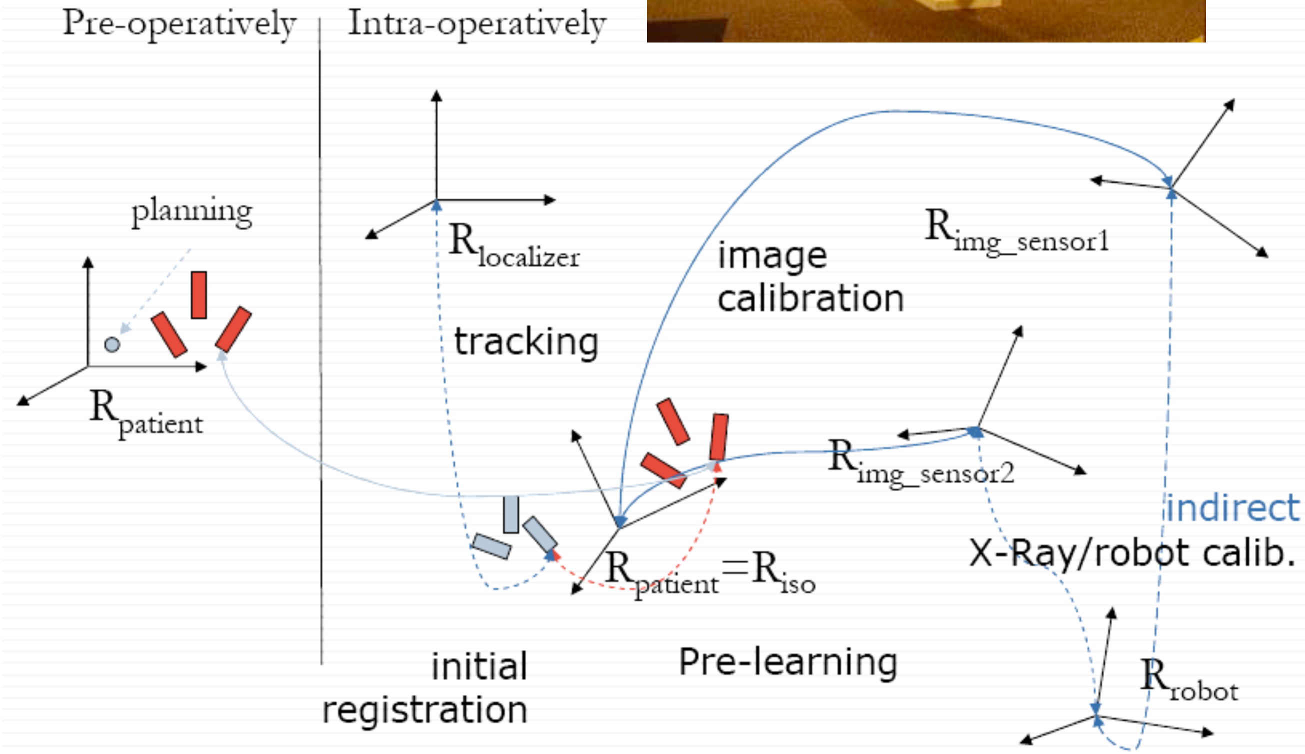


- pre-op: planning on CT data
- intra-op: a robot, x-ray sensors
  - Cyberknife [Schweikard]: indirect X-ray/robot calibration (via isocenter)
    - pre-op: planning on CT data
    - intra-op
      - indirect X-ray/robot calibration (via isocenter)
      - x-ray/DRR registration (Digitally Reconstructed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

examples (6): Cyberknife+Synchrony

non-isocentric beam generation mode





- 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
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