Medical Robotics

Robot Registration

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April 21, 2017
registration consists in determining geometric relationships between two reference frames

robotic registration essentially consists in transferring surgical plans to the coordinate system of the robot

tools calibration (C), tracking (T), registration data (R) using patients data and external objects requires intrinsic robot calibration!
possible reference frames of interest

pre-operative data

intra-operative data

\[ R_{\text{patient/planning}} \]

\[ R_{\text{patient/OR}} \]

\[ R_{\text{localizer/OR}} \]

\[ R_{\text{img\_sensor/OR}} \]

\[ R_{\text{robot/OR}} \]
devices

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

- imaging sensors (real-time modalities)
  - fluoroscopy, ultrasound, digital x-ray
registration basics

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

• select the feature $^A{F}$ in $R_A$ and $^B{F}$ in $R_B$

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

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

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

rigid registration (case of a single feature)

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

• determine $^A{R}_B$ and $^A{p}_{AB}$ s.t.

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

\begin{align*}
\text{known correspondence} & \quad \text{unknown correspondence}
\end{align*}

\text{idea:} \text{ 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: $^A F_0 = A^T_B(B^F)$ (with $^A F = \{^A f_i\}$)

2. identification of the closest points on $M$: $^A F_0 = \text{closest}(^A F_0, M)$ (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 threshold $\tau$

* the function to be minimized is $d(^A F, A^T_B(B^F)) = \frac{1}{N} \sum_{i=1}^{N} ||^A f_i - A R_B B f_i - A p_{AB}||$, where points $^A f_i$ correspond to points $^B f_i$ (determined by the operator ‘closest’)

* the error at $k$-th step is $e_k = \frac{1}{N} \sum_{i=1}^{N} ||^A f_{ik} - A R_B^k B f_i - A p_{AB}^k||$

* 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 or 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

Pre-operatively

Intra-operatively

Planning

Iterated image registration

$R_{\text{patient}}$

$R_{\text{isocenter}}$

$R_{\text{img-sensor1}}$

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

X-Ray calibration

X-Ray/Iso calibration

Set-up

Robot/Iso calibration

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• 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

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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


