Deformable Image Registration

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Master 2 MISS 2018

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Goals

- Future jobs: engineer, research, application
- Know how/why to read research papers
- Be ready to code
- Understand context
- Understand notation
- Comparison with other works
- Validation

For next session: prepare 5 questions
Outline

- Introduction, principles
- Method n°1 : Demons
- Evaluation
- Method n°2 : B-Splines
- Method n°3 : TPS (Thin Plate Spline)
- The « sliding » problem
- Spatio-temporal deformable registration
- Conclusion
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Deformable Image Registration (DIR)

Algorithm

Input = two images (reference & moving)

Output = deformation map

Fixed Image (reference)  Moving Image
\[ \phi(x) = x' \]
\[ \phi = \text{deformation} \]
Deformation Vector Field

DVF is used to:
- To quantify the motion in ROIs
- To deform an image or a contour

DVF can be stored:
- With one vector by pixel
- With a function: B-Spline, RBF …

\[ T(p) : R^3 \rightarrow R^3 = p + u(p) \]

\[ p = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad u(p) = \begin{pmatrix} dx \\ dy \\ dz \end{pmatrix} \]
In DIR we trust …

**Rigid** image registration
- Find rotation and translation
- 6 numbers for 3D images

**Deformable** image registration
- Find deformation
- Thousand of numbers (even more !)
- One vector at each pixel
Léon Bérard cancer center (CLB)

22 000 patients/year

Radiation Therapy department
- ~2800 patients/year
- Technical facility: 5 Linacs, 1 CT scanner, 2 on-board scanners (CBCT), Tomotherapy, Cyberknife

www.centreleonberard.fr
Radiation therapy

- A major cancer treatment (2/3 of patients)
- Use radiation to kill cancer cells.
  - High energy x-ray
  - Alternative with proton, carbon (in development)
- Challenge:
  deliver maximum dose to target, while sparing healthy surrounding tissue
Image guided radiation therapy

Make heavy use of imaging

Treatment planning:
- Performed on CT
- Use fused MRI, PET
- Advanced development with 4D CT

In room image guidance
- CBCT Cone Beam CT
- US image guidance
- Video, surface based
- Future: embedded MRI
Image guided radiation therapy

Heavily computer based.

- Simulation to predict dose distribution on planning CT image
- Segmentation (atlas based)
- Registration, planning multimodality
- Reconstruction motion compensated (in room)
- Registration, in room

Image registration
Lung cancer

- 12.7% of cancers (worldwide)
- 1 350 000 new cases / year (worldwide)
- 1st mortality cause by cancer, 1 180 000 / year (worldwide)
- ~90% due to smoking …
- 5 year survival (2006, France): 13% (M) 18% (W)

Treated by surgery if possible, else radiotherapy & chemotherapy
Example 1

Initial planning CT

CT after 2 weeks
Example 1

Differences after **rigid** registration
Example 1

Final differences after deformable registration
DIR for atlas-based segmentation
DIR for atlas-based segmentation
4D CT – breathing motion
Deformable image registration

It is an **ill-posed** problem

- Well-posed = solution exists + the solution is unique + the solution depends continuously on the data
- Hard to solve, tradeoff

**Tradeoff:**

- **Image similarity**: can always match any pixel to any other one (Mutual Information, correlation coefficient, correlation ratio …)
- **Transformation regularity**: is the deformation plausible?
Generic model: optimisation

\[
T_{\text{opt}} = \operatorname{arg}_{T} \max \left[ \alpha E_{\text{sim}}(A, B, T) + (1-\alpha) E_{\text{reg}}(T) \right]
\]

\(A, B\) = the two images to register (reference & moving)
\(T_{\text{opt}}\) = the sought optimal transformation
\(E_{\text{sim}}\) = similarity measure
\(E_{\text{reg}}\) = regularization measure of \(T\)
\(\alpha\) = tradeoff parameter
\(\operatorname{arg}_{T} \max\) = optimization algorithm
Deformable Image Registration (DIR)

**Image Similarity**

\[ E_{sim}(A, B, T) \]

- Quantify the similarity between I and J deformed by T
- Allow to compare different deformations T

**Regularization**

\[ \uparrow E_{reg}(T) \]

- T should be smooth enough (no trajectory crossing, …)
- T should be **diffeomorphic** (one-to-one, continuous, inverse continuous)

**Optimization** procedure:

\[ \arg_T \max \]

- How to find the best T?
- Iterative process; strategy to search + stopping criteria
Deformable Image Registration (DIR)

Numerous algorithms
- Demons [Thirion 1998]
- B-Spline free form deformation [Rueckert 1999]
- Linear Elastic [Christensen 2001]
- … tens others methods or developments (still continuing)

Conclusion
- Hard, useful, numerous algorithms
- No “general” solution (such as in rigid), application dependent
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Example 1: the « Demons » algorithm

Method proposed by [Thirion1998] [Pennec1999]

- Popular
- “Simple” to implement
- A posteriori explanation
- Numerous developments
Principle
Principle

- Iterative algorithm
- At each iteration
  - Step 1: estimate the deformation vector field (DVF)
  - Step 2: regularize the DVF
- Stopping criteria to determine

Images to register

Displacement at x

DVF

\[
\begin{align*}
\phi(x) &= x + u(x) \\
I_1 & \quad I_2 \\
u(x)
\end{align*}
\]
Principle: step 1

- Displacement evaluation at every pixel \( x \)
- This displacement is:
  - It is \( \parallel \) to the image \( I_1 \) gradient (\( I_1 \) is the moving image)
  - Proportional to pixel grey level difference between the 2 images at location \( x \).
- « Small » displacement, bounded by \( 1/(2\alpha) \)
- Alpha = user parameter

\[
\nabla D_{SSD}(x, u) = \frac{I_2(x + u(x)) - I_1}{\parallel \nabla I_1(x) \parallel^2 + \alpha^2 (I_2(x + u(x)) - I_1)^2} \nabla I_1(x)
\]
Explanation

Intensity (grey level)

Spatial (pixel x)

Fixed image

Moving image

Current pixel
Explanation

Intensity (grey level)

Spatial (pixel x)

Fixed image

Moving image

Gradient
Explanation

Intensity (grey level)

Spatial (pixel x)

Desired Displacement

Gradient
Explanation

Intensity (grey level)

Spatial (pixel x)

Gradient
Explanation

Current Estimation

Intensity (grey level)

Spatial (pixel x)

Gradient
Intensities (grey level) and spatial (pixel x) relationships are illustrated in the graph. The gradient is highlighted at a specific point to demonstrate how intensities change with spatial coordinates.
Explanation

Intensity (grey level)

Spatial (pixel x)

Gradient
Explanation

Intensity (grey level)

Spatial (pixel x)

Gradient
Principle: step 1

\[ \nabla D_{SSD}(x, u) = \frac{I_2(x + u(x)) - I_1}{\|\nabla I_1(x)\|^2 + \alpha^2 (I_2(x + u(x)) - I_1)^2} \nabla I_1(x) \]
Principle: step 2

- Regularize the DVF with a Gaussian filter (need parameter sigma)

- Possible to regularize:
  - The total displacement (previous + total)
  - The current displacement only (fluid registration)

$$u_{i+1}(x) = G_{\sigma} \left( \nabla D_{SSD}(x, u_i) \circ u_i(x) \right)$$

$$G_{\sigma}(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{x^2}{2\sigma^2}}$$
Practical considerations

- Iterative algorithm

- Estimation of the image gradient $\nabla I_1(x)$
  - Only once
  - One 3D vector by pixel

- Displacement estimation at each pixel
  - One 3D vector by pixel for the current field
  - One 3D vector by pixel for the current displacement $\nabla D_{SSD}(x, u_i)$
Practical considerations

3D Gaussian filter on the DVF
- Separable, with 1D Gaussian filter
- [Deriche 1993]
- Apply to dimensions 1, 2, 3 on all vector components: 9 loops

Stopping criteria
- Number of iterations (by experiment)
- DVF norm < threshold
- etc …

Interpolation of non integer coordinates
- Nearest neighbours
- Linear
- Other …
Practical considerations

Computing time linear to the number of pixels
« Crop » the images
Practical considerations

Computing time linear to the number of pixels
« Crop » the images
50% time gain!
Can be automatized (segmentation)
Practical considerations

Computing time linear to the number of pixels

Images sub-sampling
- = increase the « spacing » (2mm pixel size instead of 1mm)
- In 3D, if divide by 2 : 8 times less pixels

Multi-scale strategy
Interpretations

[Thirion1998] relates Gaussian filtering to the diffusion of heat in homogeneous material, by analogy with the Maxwell 's demons.

[Cachier2004] This criterion was shown to be an approximation of a second order gradient descent of the SSD

[Bro-Nielsen1996] showed that such Gaussian filtering may be considered as an approximation of the linear elastic filter used in the viscous-fluid modelling.
Variants

**Symmetric Demons**

[Wang2005]


\[
\mathbf{u} = (m - s) \times \left( \frac{\nabla s}{|\nabla s|^2 + \alpha^2 (s - m)^2} + \frac{\nabla m}{|\nabla m|^2 + \alpha^2 (s - m)^2} \right)
\]

- Improve speed by 40% (longer, but fewer iteration)
- Maybe more robust
Figure 1. Illustration of asymmetric registration and inverse consistency error. Point A (in image $I$) and B (in image $J$) are matching points. $V$ is computed by registering $I$ to $J$. $U$ is computed by registering image $J$ to image $I$. (a) After imperfect asymmetric registrations, point A moves to point $A'$ and point B moves to point $B'$. (b) Using $U$, $A'$ will be moved to $A''$. Similarly, $B''$ is $B'$ moved by using $V$. The distance from $A$ to $A''$, and from $B$ to $B''$, are the inverse consistency errors.
Fast inverse consistent Demons

[Yang et al 2008]

- The two images were symmetrically deformed toward the other until both deformed images are matched.
- This principle is called “consistent” because it insure implicitly that the inverse deformation field exist.
- The computation time is typically higher than conventional Demons, but lower than Symmetric Demons.
- Convergence speed seems to be improved by this version.
Diffeomorphic Demons

[Vercauteren et al 2007, 2009]

- Modification to constrain the deformation to be a *diffeomorphism*

- *Diffeomorphism*: that is a continuous, one-to-one, onto, and differentiable mapping.

- Such kind of deformation maintains the topology and guarantees that connected regions of an image remain connected

- This approach leads to similar results in term of accuracy than the ones given by the initial approach, but with smoother transformation.
Conclusion

« Demons » algorithm
- Simple, very used, efficient
- Assumption on pixel intensity conservation (SSD)
- Smooth transformation but non necessarily physically plausible
- GPU implementation also available
- Still studied
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How to evaluate the result of DIR algorithm?
Evaluation

How to evaluate?

- No gold-standard
- Use of phantom: real or numeric
- Consistency (symmetry, negative Jacobian)
- Use of manual anatomical landmarks,
  - Distances between reference and deformed landmarks
  - TRE = Target Registration Error
- Overlap of segmented structures (DICE coefficient)
Dice Similarity Coefficient (DSC)

Quantifier le chevauchement (overlap) entre deux structures

\[ DSC(S, T) = \frac{2|S \cap T|}{|S| + |T|} \]

Index de Jacquard

\[ JSC(S, T) = \frac{|S \cap T|}{|S \cup T|} \]
Evaluation

Examples:
[Sarrut et al. IEEE TMI 2007]  [Brock et al IJROBP 2010]  [Murphy et al IEEE TMI 2011]

“EMPIRE “challenge:
Evaluation of Methods for Pulmonary Image Registration

- 20 thorax inhale/exhale pairs of images
- 34 teams worldwide
- TRE error : ~10 first <1 mm and ~20 first <2mm
- (we were 1.5mm, 14/34)
Evaluation - conclusion

Evaluation with TRE or structures overlap: « offline »
- Time consuming
- Not perfect (what happens in areas within landmarks?)

If DIR is proposed in clinic, how to evaluate « online »?