



e-Seminar #20

Introduction to Biomedical Image Registration and the Parallel Framework for Image Registration



Presenter: Daniele Tartarini (The University of Sheffield) 9 December 2021

The e-Seminar will start at 3pm CET / 2pm GMT



Moderator: Tim Weaving (University College London)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 675451



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The e-Seminar series is run in collaboration with:









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Introduction to Biomedical Image Registration and the Parallel Framework for Image Registration



Daniele Tartarini

(The University of Sheffield

9 December 2021

Welcome!



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14/12/2021

Outline

- Introduction to Image registration
- Quality measures/cost functions
- Introduction on pFIRE
 - Activity in Compbiomed
 - Refactoring and exascale
- Example of applications







Image Acquisition Modalities







MNR

- CT Computerised Tomography. Based on X-ray images
- PET/SPECT Single-Photon Emission Computed tomography. Uses gamma rays and requires radioactive tracer
- MNR/MRI- Magnetic Nuclear Resonance
- Ultrasound. High frequency sound waves







PET-MRI



Multi Modality Registration





Diffusion Tensor Imaging





Diffusion Weighted Imaging



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Multi modality image registration



PET



CT







Need for Registration

- Multi modality registration (e.g. MRI-PET)
- Patient moving during session: CT/MRI scan
- Imaging of patients at different sessions
- Acquisition of time dependent series
- Morphological chances due patient growth
- Deformations due to disease evolution (e.g.)
- Scanner calibration and geometrical distortion
- Superposition of biomechanical modelling meshes





An example: CT of thorax

Fixed image



Moved image



<u>Image registration</u>: finds the mathematical function that maps the moved image onto the reference image





An example: CT of thorax

Overlap fixed/moved image in RGB channels



Registration Map



The mapping function can be represented as a field of vectors joining corresponding points.





The source (or moved) image *m* is registered to the target (or fixed) image *f*.

We search for points in *m* which match points in *f*.







 In 3D the mapping function can be expressed in the form of 3 functions.

$$X' = U(X, Y, Z) + X$$
$$Y' = V(X, Y, Z) + Y$$
$$Z' = W(X, Y, Z) + Z$$

- The mapping is one-to-one.
- *u*, *v*, *w* are displacement functions.
- For simplicity registration will be illustrated with 2D examples. Theory translates to 3D





Special mappings

• Translation

 $u = a_1$ $v = a_2$

• Rigid rotation with translation

 $u = a_1 + x \cdot \cos(\theta) + y \cdot \sin(\theta)$ $v = a_2 - x \cdot \sin(\theta) + y \cdot \cos(\theta)$

• Affine

$$u = a_{11} + a_{12} \cdot x + a_{13} \cdot y$$
$$v = a_{21} + a_{22} \cdot x + a_{23} \cdot y$$





Non-linear Mapping

- The mapping function is computed on a grid of points (nodes) spaced *D* pixels apart.
- Same approach as in FEM analysis
- The $a_x a_y$ are the values of the mapping at the grid nodes.
- Values of the mapping between nodes are obtained by interpolation with local basis functions.

$$u = \sum_{i}^{i} a_{xi} \phi_i(x, y)$$
$$v = \sum_{i}^{i} a_{yi} \phi_i(x, y)$$







• An example of a local basis function is the bi/tri-linear interpolation function.

$$\phi_i(x, y) = (1 - \left| \frac{x - x_i}{D} \right|) (1 - \left| \frac{y - y_i}{D} \right|) \qquad \left\{ -1 <= \left(\frac{x - x_i}{D}, \frac{y - y_i}{D} \right) <= 1 \right\}$$

but other functions may be used (e.g. cubic, hermite ...)

- Each of these functions is centred on each node of the grid, coordinates x_i, y_i.
- Partition of unity holds





The Mapping Function

Assuming image intensities are the same at corresponding points

$$x' = u(x, y) + x$$

$$y' = v(x, y) + y$$

u and v are functions of coordinates

The mapping function is

f(x,y) = m(x,'y') = m(u(x,y) + x, v(x,y) + y)







The Registration Equation

Using the Taylor series expansion and rearranging the terms:

$$f(x,y) = m(x,y) + u(x,y) \left(\frac{\partial m(x,y)}{\partial x}\right) + v(x,y) \left(\frac{\partial m(x,y)}{\partial y}\right) + \dots$$

The registration equation becomes:

$$f(x,y) - m(x,y) = \frac{1}{2} \left[u(x,y) \left(\frac{\partial f(x,y)}{\partial x} + \frac{\partial m(x,y)}{\partial x} \right) + v(x,y) \left(\frac{\partial f(x,y)}{\partial y} + \frac{\partial m(x,y)}{\partial y} \right) \right] + \dots$$

Note that the images become independent from u, v Simplifying calculations



D.C. Barber et al. / Medical Image Analysis 11 (2007)



The Registration Equation

Higher order terms are truncated so it is accurate only for small values of u, v.

Expanding the basis functions:

$$u = \sum_{i} a_{xi} \phi_i(x, y) \qquad v = \sum_{i} a_{yi} \phi_i(x, y)$$

 $f(x,y) - \mathbf{m}(x,y) = \frac{1}{2} \left[\sum_{i} a_{xi} \phi_{i}(x,y) \left(\frac{\partial f}{\partial x} + \frac{\partial m}{\partial x} \right) + \sum_{i} a_{yi} \phi_{i}(x,y) \left(\frac{\partial f}{\partial y} + \frac{\partial m}{\partial y} \right) \right] + \dots$

The equation is linear in coefficients a_{ij} One equations per voxel





Finding Displacements Map

Organizing the equation in Matrix form

$$f-m=Ta$$

The equation is usually overdetermined

- **f**, **m** are vectors of size N
- **T** is a matrix of N*2P elements
- *a* is a vector of size 2P

$$a = (T^t T)^{-1} T^t (f - m)$$





Solution issues

The problem is ill-posed and ill-conditioned because the matrix

 $(T^{t}T)$ in the equation $a = (T^{t}T)^{-1} T^{t}(f - m)$

The solution is very sensitive to noise and a constraint is required.

A suitable constraint is imposing smoothness via Laplacian:

$$\nabla^2 u(x,y), \nabla^2 v(x,y) = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}, \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}$$

In discrete form the constraint is La = 0





Iterative Solution

$$\begin{bmatrix} \boldsymbol{f} - \boldsymbol{m} \\ 0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{T} \\ \lambda \boldsymbol{L} \end{bmatrix} \boldsymbol{a}$$

The solution is

$$\boldsymbol{a} = (\boldsymbol{T}^{t}\boldsymbol{T} + \lambda^{2}\boldsymbol{L}^{t}\boldsymbol{L})^{-1} \boldsymbol{T}^{t}(\boldsymbol{f} - \boldsymbol{m})$$

It derived form Taylor expansion so is accurate only for small displacements.

An Iterative procedure is required.

$$a_0 = (T^t T + \lambda^2 L^t L)^{-1} T^t (f - m)$$

$$a_1 = (T^t T + \lambda^2 L^t L)^{-1} T^t (f - m(a_0))$$

$$a_2 = \dots$$





Quality measures/Cost functions

Cost functions measure the registration quality

• Sum of Squares differences for images based on intensity

$$Q = \sum_{voxels} (f - m(a))^2$$

• Mutual information

$$MI(A,B) = \sum_{a,b} p_{AB}(a,b) \cdot \frac{\log(p_{AB}(a,b))}{p_A(a) \cdot p_B(b)}$$

is currently considered a gold standard measure of image similarity.





Sum of Squares

The Sum of Squared differences criterion is computationally efficient but it is sensitive intensity difference.

An intensity image can be converted to a binary image augmenting dimensionality:



 $\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y}) \dashrightarrow \boldsymbol{f}_{\mathrm{b}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{s})$

Mapping between binary images is not unique and need extra constraints are needed (e.g. smoothness)

$$f_{\rm b}(x,y) = m_{\rm b}(x+u,y+v)$$

$$f_{b}(x,y) - m_{b}(x+u,y+v) = \frac{1}{2} \left[u(x,y) \left(\frac{\partial f_{b}(x,y)}{\partial x} + \frac{\partial m_{b}(x,y)}{\partial x} \right) + v(x,y) \left(\frac{\partial f_{b}(x,y)}{\partial y} + \frac{\partial m_{b}(x,y)}{\partial y} \right) \right] + \dots$$



(Barber DC, Hose R, J. Med. Eng & tech., 2005)



Mutual Information

The Mutual information MI(A,B) measures the independence of images A and B as the distance between the joint distribution $p_{AB}(a, b)$ and the distribution associated to the case of independent images (Kullbacl-Leibler measure).

$$MI(A,B) = \sum_{a,b} p_{AB}(a,b) \cdot \frac{\log(p_{AB}(a,b))}{p_A(a) \cdot p_B(b)}$$

The MI of the image intensity values of corresponding voxel pairs in mapping is maximal if the images are geometrically aligned.

Because no assumptions are made regarding the nature of the relation between the image intensities, this criterion is very general and powerful and can be applied automatically on multi-modality images.

Considered the golden standard. Computationally expensive.





Histogram





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Joint Histogram

The Joint histogram of a perfectly registered image is concentrated on a line

h(a,b)

is the number of pixels having grey value a in image A and b in image B









In this case image B is rotated of 15° The histogram pattern is dispersed (entropy)



Joint Histogram

joint histogram (x,y) Œ 200 1.52 10000 8000 6000





Joint Histogram

Entropy increases with rotation







Mutual Information Rotations







[1.3104, 0.3076, 0.2977, 0.2864, 0.2808, 0.2757, 0.2737];



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pFIRE: Parallel Framework for Image REgistration

Derived by published work of RD Hose and D Barber

Iterative registration algorithm

Implements Mutual Information

Size of mesh D is initially image_dimension/4; iteration is repeated halving it and until mutual information does not decrease

Stopping criterion when displacements at iteration << voxel size Computation of lambda depends on MI

Solver Krylov subspace implemented by PETSc Parallel MPI implementation for HPC Optimisations are implemented accounting for matrix sparsity and efficient of MPI distribution of computation



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CompBioMed Application Incubation Program







pFIRE

# pFIRE	Docs + Getting	g Started + Installing pFIRE	View page source
Reach doca			
Getting Started	Installi	ng pFIRE	
Dependenciny Manually Building pFIRE	Currently pFIR https://github.o	E must be compiled from source. This is available com/INSIGNEO/pfire_petsc.git	e from the github repository at
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Getting S	tarted	Using the Integration	Test Suite
B Develope B Using t	r Documentation he Integration Test Suite	Along with the pFIRE library and executab tests for validation, benchmarking and val documented in detail here.	ale, the codebase also includes unit tests and integration idation of pFIRE's functionality. The use of these is
Source	Documentation	Integration Testing	
		Integration testing involves running the co comparing either to an accepted result, eit of another program (this could be an earlie	omplete program against various input data and ther in the form of predetermined result file or the output er version of pFIRE or a different image registration code).
		Integration testing for pFIRE can be perfor located in the <i>benchmarking/subdirector</i>	rmed using the pfire_benchmarking python module, y of the source code repository.
		Installation	
		Since it is provided as a standard python n python version 3.5 or later, either using pi	nodule the test suite may be installed on any system with ip or by manually running the provided setup.py:
		3 (# benchmarking # them 5 pip installuser . 40r 5 pythen3 setup.py	
		The test suite is dependent on several con installed for you automatically. If installing	mmon python packages. If using pip these should be manually it is up to you to install them.
		Once installed, the testsuite may be run u	sing the phre-integration-test command.
		Running Integration Tests	
		The integration test suite can be run eithe There are two types of test that the suite pFIRE and its predecessor (SNIRT) against	r on a single test file or on all tests in a directory tree. supports, comparison with a result file, or by running both the same test data and comparing the results.
		To run against a single configuration file, p	sass that test file as a parameter to the testsuite
		\$ pfire-integration-test /path/to/test	file.Sestconf

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FAIR-SW and best practices

Findable, Accessible, Interoperable, Reproducible Software principles

Concurrent versioning system: <u>http://github.com/INSIGNEO/pFIRE</u> Continuous Integration and deployment: TravisCI → Jenkins (MPI) Documentation as code: ReadTheDocs Documentation + UML

Distributed as Source code, Docker and Singularity images hub.docker.com/r/insigneopfire/pfire

Standard Data Formats: HDF5, DICOM, png, tiff (replaces proprietary format)



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C++ Dependencies complexity

Spack package manager



Containerization experience



Docker: Ideal for workstation. Introduced the rootless mode for MPI

Singularity better support for MPI but need to run compatible MPI implementations between container and host

pFIRE Container Architecture

pFIRE (Singularity)

Library dependencies Layer (Singularity)

OS Layer (Docker)

Evolving technology with limitations

Restrictions on the filesystem and user permissions Singularity MPI hybrid needs tweaks for performance





Computational Performance

3D CT Tibia



ShARC node specifications: CPUs: 2 x Intel Xeon E5-2630 v3@2.4GHz RAM: 64 GiB (4 GiB / core) Hyperthreading disabled

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Segmentation via registration

Reference image



Registration

Patient image



Automatic segmentation

Reference Kidney segmentation



Map contour





Methodology in Barber, D. C. 2005)



Registration Based Segmentation

Systolic flow Vessel ROI





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Spine Meshing





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CT2S pipeline including image registration

The CT2S service provides an estimate of the strength of human bone, using non-invasive medical imaging







University of Sheffield Team

Dr Alberto Marzo Dr Andrew Narracott

Dr Xinshan Li Dr Ivan Benemerito

Dr Paul Richmond Dr Daniele Tartarini





Former members: Dr A Melis, Dr Phil Tooley







Q&A

To pose a question, you can write your question in the "Questions" tab



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Thank you for participating!

...don't forget to fill in our feedback questionnaire...

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