Lecture 8
Registration with ITK

Methods in Medical Image Analysis - Spring 2020
16-725 (CMU RI) : BioE 2630 (Pitt)
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Based in part on Damion Shelton’s slides from 2006

For more info/gory detail...

- Please see the following for exhaustive detail:
  - Chapter 3 in the ITK Software Guide Book
  - Insight into Images
  - ITK Source Tree
    - Examples/RegistrationITKv4/
      - E.g. Examples/RegistrationITKv4/ImageRegistration1.cxx
  - ITK Doxygen
    - http://www.itk.org/Doxygen50/html/group__RegistrationFilters.html
  - SimpleITK:
    - http://insightsoftwareconsortium.github.io/SimpleITK-Notebooks/
      - See all the Python Registration (6x) notebooks, especially:
        - http://insightsoftwareconsortium.github.io/SimpleITK-Notebooks/Python_html/60_Registration_Introduction.html
        - https://itk.org/SimpleITKDoxygen/html/classitk_1_1Simple_1_1ImageRegistrationMethod.html
What is registration?

- The process of aligning a target image to a source image
- More generally, determining the transform that maps points in the target image to points in the source image

Transform types

- Rigid (rotate, translate)
- Affine (rigid + scale & shear)
- Deformable = non-rigid (affine + vector field)
- Many others
Registration in ITK

- ITK uses an extensible registration framework
- Various interchangeable classes exist
- Relatively easy to “twiddle” the part you’re interested in while recycling prior work
- The newer ITKv4 Registration framework is separate from the legacy framework.
  - The legacy framework follows traditional practice
  - Version 4 registration is more flexible and thus more complex
  - Use the v4 framework whenever practical
- SimpleITK recently gained registration support at v. 0.9, improved in v1.0
- For “simplified” complex registration, consider using ANTS instead:
  - http://www.picsl.upenn.edu/ANTS/
  - http://stnava.github.io/ANTs/

New in ITKv4
(ImageRegistrationMethodv4, etc.)

- New unified, improved, and fully multi-threaded optimization and registration framework (including multi-threaded metrics)
- Dense deformation fields (including a new transform that encapsulates a dense deformation field)
- Point Set registration methods (landmark or label guided registration)

- Automatic parameter scale estimation for transforms
- Automatic step-size selection for gradient-based registration optimizers
- Composite Transforms (grouping multiple transforms into a single one)
- Symmetric registration (where the Fixed and Moving images make unbiased contributions to the registration)
- New metrics for Demons and Mutual Information
- Diffeomorphic (velocity field) deformable registration
- Additional evolutionary optimizers
- Improved B-Spline registration approach available and bug fixes to old framework
- Accurately transform and reorient covariant tensors and vectors

ITKv4 Registration

- Uses a different framework than “traditional” ITK registration. The new framework is designated with a “v4” suffix.
- You must use a v4 metric and a v4 optimizer when doing a v4 registration!
- Take a look here:
- ITK source code: Modules/Registration/RegistrationMethodsv4/include/
- ITK source code: Modules/Registration/Metricsv4/include/
- ITK source code: Modules/Numerics/Optimizersv4/include/
- Pay special attention to:
  - MattesMutualInformationImageToImageMetricv4
  - DemonsImageToImageMetricv4
  - QuasiNewtonOptimizerv4 (an improved gradient descent)

Typical registration terminology

- Fixed image $f(x)$ - stationary in space
- Moving image $m(x)$ - the fixed image with an unknown transform applied
- Goal: recover the transform $T(x)$ which maps points in $f(x)$ to $m(x)$
Typical registration framework

- 2 input images, fixed and moving
- Metric - determines the “fitness” of the current registration iteration
- Optimizer - adjusts the transform in an attempt to improve the metric
- Interpolator - applies transform to image and computes sub-pixel values

Figure 8.2 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.
Both input images are transformed into a common virtual domain, which determines:

- The output resampled-image dimensions and spacing
- The sampling grid (not necessarily a uniform grid)
- Defaults to the fixed image domain

Only the Moving Transform is Optimized

Fixed Transform defaults to identity transform
- But it could be set to the result of a previous registration, etc.
ITK v4 Virtual Domain

ITK’s “Hello world” registration example

- Uses ITK’s v4 framework, but in the “typical” traditional style
- Please see the software guide (Book 2, Section 3.2) for code specifics
- I am going to cover what each piece does, not look at code per se
ITK’s “Hello World” Example: Flow Chart for Everything

Input images

- 2D floating point
- Floating point avoids loss of precision problems with integer pixel types
Transform

- TranslationTransform
- Permits *translation only* in 2D

- ITKv4 still uses the same legacy transforms
- ITKv4 also supports new *composite transforms*:
  - Two or more successive transforms...
  - Combined into a single transform object
  - Can initialize with one transform and optimize another

Metric

- MeanSquaresImageToImageMetricv4
- Sum of squared differences between 2 images on a “pixel-by-pixel” basis
  - Remember that both images are transformed to the virtual domain before doing the comparisons
- A bit naïve
- Works for 2 images that were acquired with the same imaging modality
**Optimizer**

- RegularStepGradientDescentOptimizerv4
- Follows the derivative of the metric
- Step size depends on rapid changes in the gradient’s direction
- Step size eventually reaches a user-defined value that determines convergence

**Interpolator**

- LinearInterpolateImageFunction
- Fast and conceptually simple
Wrapper

- ImageRegistrationMethodv4
- Combines all of the previous classes into a master class

```cpp
registration->SetMetric( metric );
registration->SetOptimiser( optimiser );
metric->SetFixedInterpolator( FixedInterpolator );
moving->SetMovingInterpolator( MovingInterpolator );
```

- Registration method automatically instantiates its own internal transform
  - Based on its template parameters

Other steps

- Read the input images
- Setup the virtual domain
  - Defaults to the fixed image
- Set the region of the fixed image the registration will operate on
  - Useful for ignoring bad data
- Initialize the transforms
  - Fixed transform defaults to identity
- Setup multi-level registration
  - Like image-pyramids, but better
  - Defaults to a single level
- Use a C++ try/catch block to avoid crashing on errors
- Twiddle the optimizer for best performance

*may involve pain and suffering
Hello world input

Figure 8.3 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.

X & Y translation vs. time

Figure 3.7 (left) from the ITK Software Guide Book 2, Fourth Edition, by Hans J. Johnson, et al.
Registration results

- After registration converges/terminates, you recover the optimized transform with:

  ```
  registration->GetTransform()
  ```

- For the Hello World example there are 2 parameters, X & Y translation

- If you used a separate initial moving transform, create a composite to get the total transform:

  ```
  outputCompositeTransform->AddTransform(
      movingInitialTransform);
  outputCompositeTransform->AddTransform(
      registration->GetModifiableTransform());
  ```
Double checking results

- Use ResampleImageFilter to apply the transform for the fixed and moving images
- Take the outputs, and compute their difference
- In this case, just subtract the registered images
  - Good registration results in nothing much to see

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Image comparison

![Registered moving image](image1)
![Difference before registration](image2)
![Difference after registration](image3)

Figure 8.4 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.
Keeping tabs on registration

- Registration is often time consuming
- It’s nice to know that your algorithm isn’t just spinning it’s wheels
- Use the observer (`\texttt{ITK::Command}`) mechanism in ITK to monitor progress
  - ITK software guide, book 1: 3.2.6 and book 2: 3.4
- We’ll see this again later, when we discuss how to write your own ITK filters
  - `\texttt{ITK::ProgressEvent}` is one example

Observer steps

- Write an observer class that will process “iteration” events
  - (Just copy some code from an example)
- Add the observer to the optimizer
  - As a generic note, observers can observe any class derived from `\texttt{ITK::Object}`
- Start registration as usual
Things observers can do

- Print debugging info
- Update GUI
- Other small management functions
- *Should not* do anything too processor intensive

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**ITK v4 Registration Observer**

![ITK v4 Registration Observer Diagram](image)

Figure 3.9 from the ITK Software Guide Book 2, Fourth Edition, by Hans J. Johnson, et al.
Multi-modality registration

- Remember how I said sum-of-squares difference is relatively naïve?
- Mutual information helps overcome this problem
- Section 3.5 shows how to implement a simple MI registration
  - Note that Mattes MI is usually easier to use than Viola-Wells MI

Notes about the MI example

- Significantly, largely the same piece of code as Hello World
- Mutual Information is a metric, so we can keep the optimizer, the interpolator, and so on
- Majority of differences are in tweaking the metric, not in rewriting code
MI Inputs

T1 MRI
Proton density MRI

Figure 8.9 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.

MI Output: Image Comparison

Before
After
This is an example of a checkerboard visualization

Taken from Figure 8.10 of the ITK Software Guide v 2.4, by Luis Ibáñez, et al.
Centered transforms

- More natural (arguably) reference frame than having the origin at the corner of the image
- Big picture is not appreciably different from other rigid registrations
- But, for the moment there are implementation complexities and differences, see 3.6

An aside: “Twiddling”

- A common criticism of many/most registration techniques is their number of parameters
- A successful registration often depends on a very specific fine-tuning of the algorithm
- “Generalized” registration is an open problem
Multi-Resolution registration

- Useful to think of this as algorithmic “squinting” by using image pyramids
- Start with something simple and low-res
- Use low-res registration to seed the next higher step
- Eventually run registration at high-res
- Also called “coarse to fine”

Multi-resolution idea

Figure 8.36 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.
Image pyramids

Optimization

- Parameter dependency rears its ugly head
- You often/usually need to adjust optimizer parameters as you move through the pyramid
- You can do this using the Observer mechanism
Multi-resolution example

- Again, mostly the same code as Hello World
- Multi-Resolution is now built into all of ITKv4 registration, so no need for extra classes or image pyramids

Benefits of multi-resolution

- Often faster
- More tolerant of noise (from “squinting”)
- Minimizes initialization problems to a certain extent, though not perfect
Multi-resolution

- Remember, at large (high) scale only large objects are visible
- Higher scale is higher in the image pyramid
  - So higher scale has lower resolution
- Lower scale is lower in the image pyramid
  - So lower scale has higher resolution

See the software guide for...

- Detailed list of:
  - Transforms
  - Optimizers
  - Interpolation methods
- You’re encouraged to mix and match!
Deformable registration

- Three common techniques:
  - Finite element: treat small image regions as having physical properties that control deformation
  - Bsplines: deform a mapping grid
  - Demons: images are assumed to have iso-intensity contours (isophotes); image deformations occur by pushing on these contours

Model based registration

- Build a simplified geometric model from a training set
- Identify parameters that control the characteristics of the model
- Register the model to a target image to adapt to a particular patient
Model based, cont.

- Uses the Spatial Objects framework for representing geometry
- Useful because it derives analytical data from the registration process, not just a pixel-to-pixel mapping

Model-based example

Note: This is what we want, NOT the output of an actual registration

Figure 8.60 from the ITK Software Guide v 2.4, by Luis Ibáñez, et al.
Model-based reg. schematic

Model-based registration: Warning!

- ITK does not yet directly support generic model-based registration “out of the box”
- ITKv4 does support point-set to image registration
- Otherwise, model-based reg. requires writing your own custom ITK transform, with new parameters
  - Transform’s new parameters → Spatial Object parameters
  - You must individually map your custom transform’s new parameters to the specific spatial object parameters you want to allow registration to adjust
  - This isn’t too complicated if you know what you’re doing
  - Search Insight Journal for examples
Speed issues

- Execution time can vary wildly
  - Optimizer (more naïve = faster)
  - Image dimensionality (fewer = faster)
  - Transform (fewer DOF = faster)
  - Interpolator (less precise = faster)

Take home messages

- Exactly what parameters do what is not always obvious, even if you are familiar with the code
- Successful registrations can be something of an art form
- Multi-resolution techniques can help
- Work within the framework!