Geometry Description and Mesh Construction from Medical Imaging

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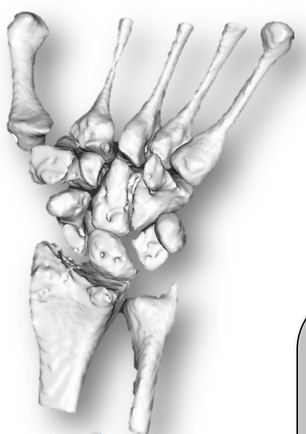
Myself

- Researcher @ CNR-IMATI
  - CNR – National Research Council
  - IMATI – Institute of Applied Mathematics and Information Technologies
  - Pavia, *Genova*, Milano
- Ph.D in Mathematics – University of Genova (IT)
- Main research interests
  - Computer Graphics
  - Numerical geometry processing
  - Meshless methods
  - Numerical & geometric aspects of PDEs
    - Heat diffusion equation and related equations
    - …

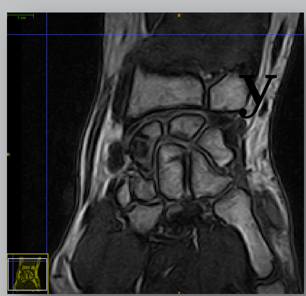
Our overall goal

- **Co-register a biomedical atlas with the MR images of a given patient** in order to
  - infer a segmentation & semantic annotation of the patient data
  - extract geometric representations of the segmented data
  - apply PDE-based & patient-specifc simulation to single subparts
  - ...

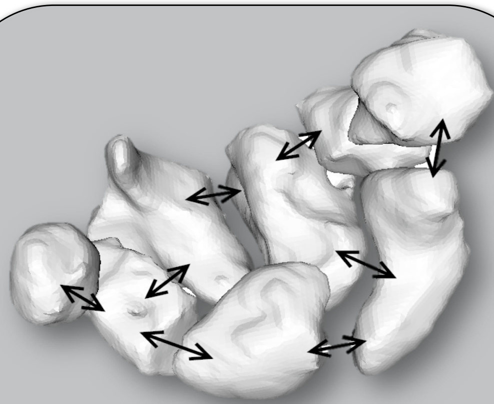
Our overall goal



Atlas



MRI data



Segmentation

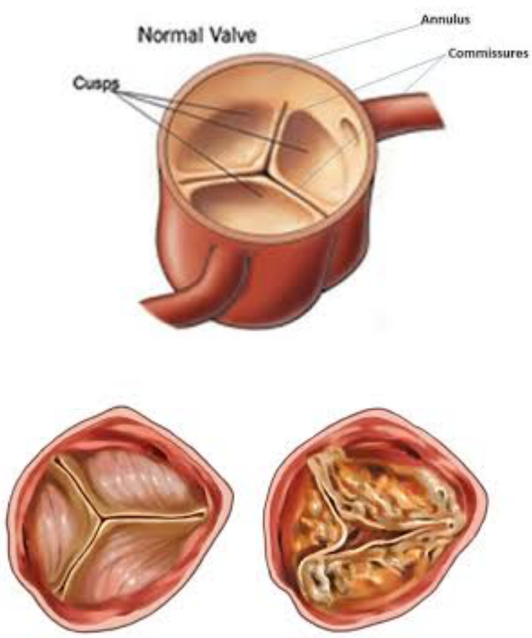
Fup(i) - base [%]	*capitate*	*hamate*	*lunate*	*pisiform*	*scaphoid*	*trapezium*	*trapezoid*	*triquetal*
capitate	-	10.2	-58.3	-	-44.2	-	-13.6	57.4
hamate	12.2	-	-48.2	-	-	-	-	-7.5
lunate	-58.2	-48.2	-	-	-17.3	-	-	-60.3
pisiform	-	-	-	-	-	-	-	-44.7
scaphoid	-44.1	-	-17.3	-	-	-	-19.5	-
trapezium	-	-	-	-	-34.9	-	-60.1	-
trapezoid	-12.7	-	-	-	-19.6	-60.1	-	-
triquetal	57.2	-7.5	-60.4	-44.1	-	-	-	-

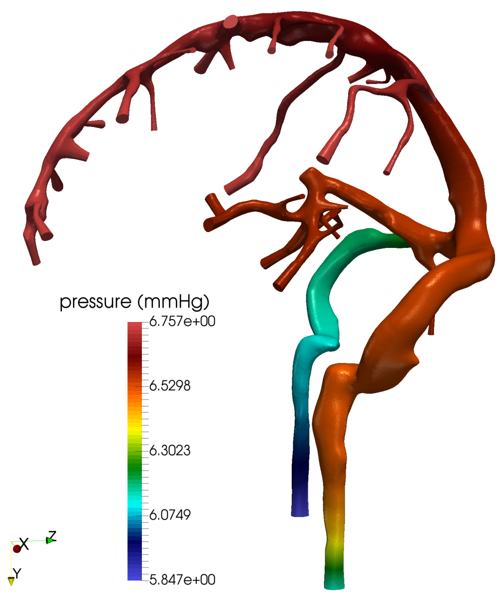
Semantics

Motivations

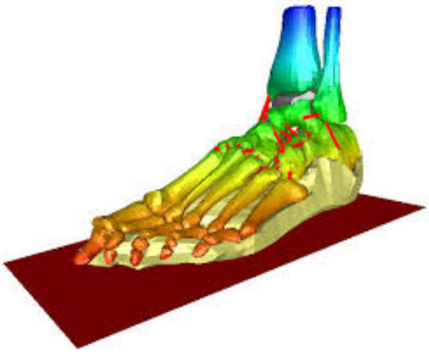
- **Patient specific simulation**
  - Imaging ➪ Reconstruction of geometry ➪ Meshing ➪ PDE solution
  - Very complicated geometries ➪ very expensive meshing procedure
  - Mesh quality influences the quality of the solution and the reliability of the simulation
- **Examples of patient-specific simulations**
  - Haemodynamics ➪ Prevention of atherosclerosis
  - Biomechanics of the foot ➪ Reduction of diabetic ulceration risk

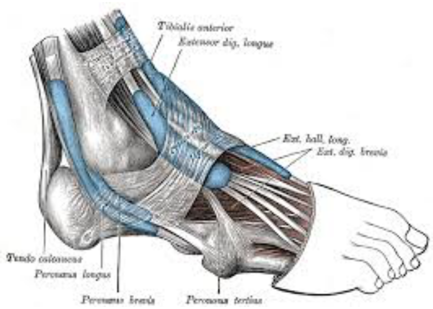
Example: haemodynamics





Example: biomechanics

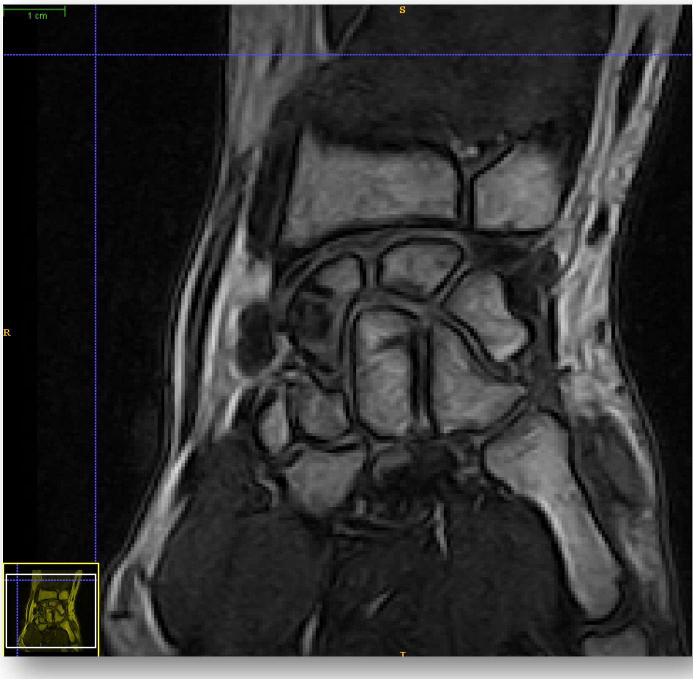




Input

- Our input/processed data will be "heterogeneous"
  - 2D images
  - volumetric bio-medical data: eg., magnetic resonance images
  - segmented volumetric 3D data
- We will work with
  - 2D and 3D regular grids (voxel grids)
  - triangle meshes
  - tetrahedral meshes

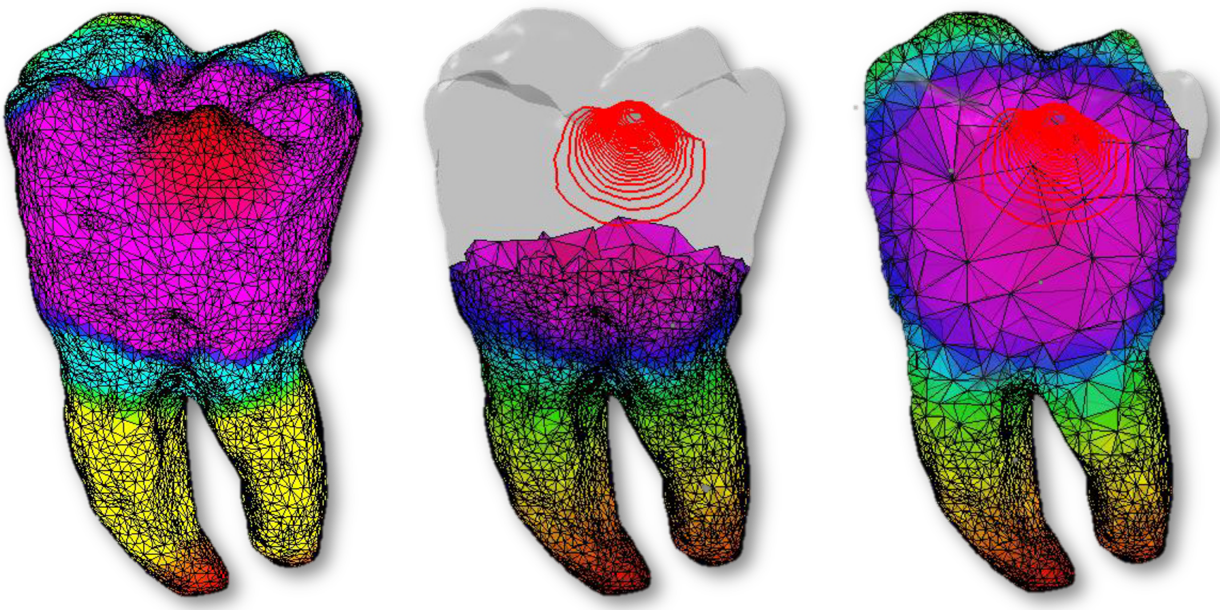
MRI images



MRI images: stack of 2D images in DICOM format

MRI image are courtesy of PLSV Ligurian Regional Hub for Life Sciences & UNIGE-DiMI, Genova

TIN & Tet meshes

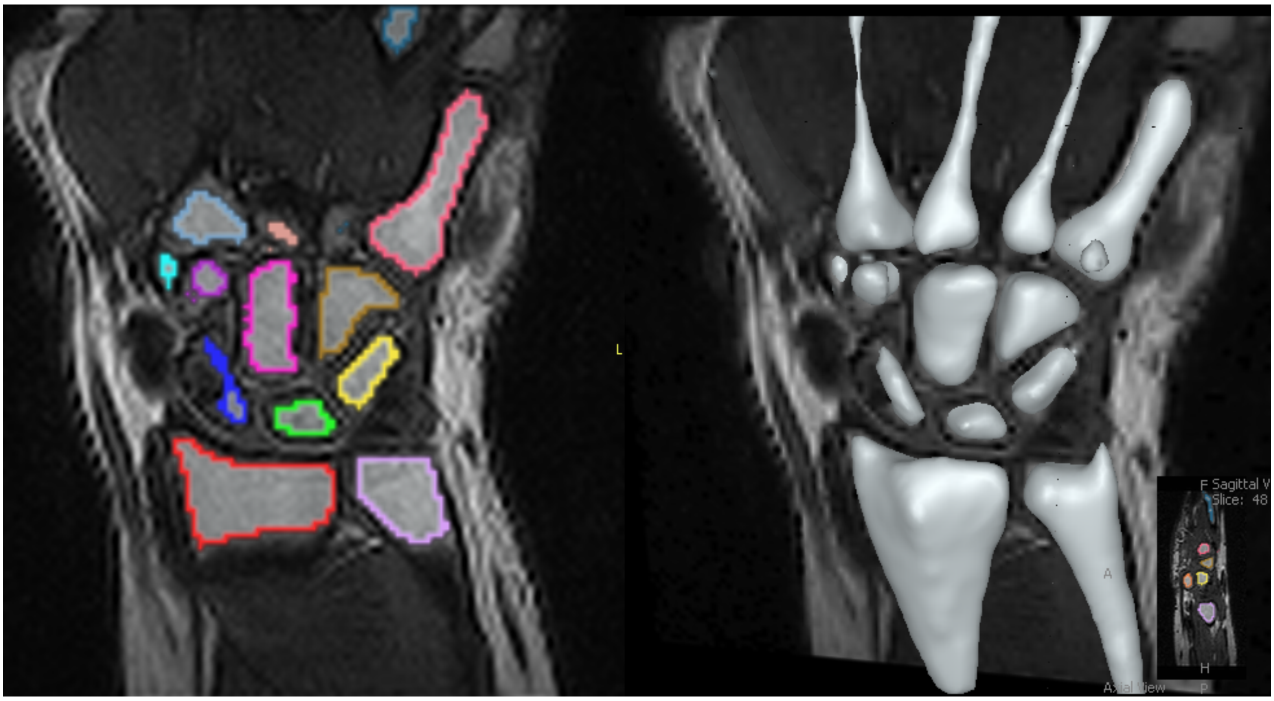


Triangle mesh **Tetrahedral meshes**

“Biomedical” Atlas

- **“Biomedical” Atlas**
  - – Pre-segmented image
    - by considering neighborhood relationships among different parts of an anatomical structure to be reconstructed;
    - by constructing a good quality mesh for a model structure
  - – each segment is marked with a sematic label;
  - – anatomical structures have intrinsic structural similarities.

“Biomedical” Atlas

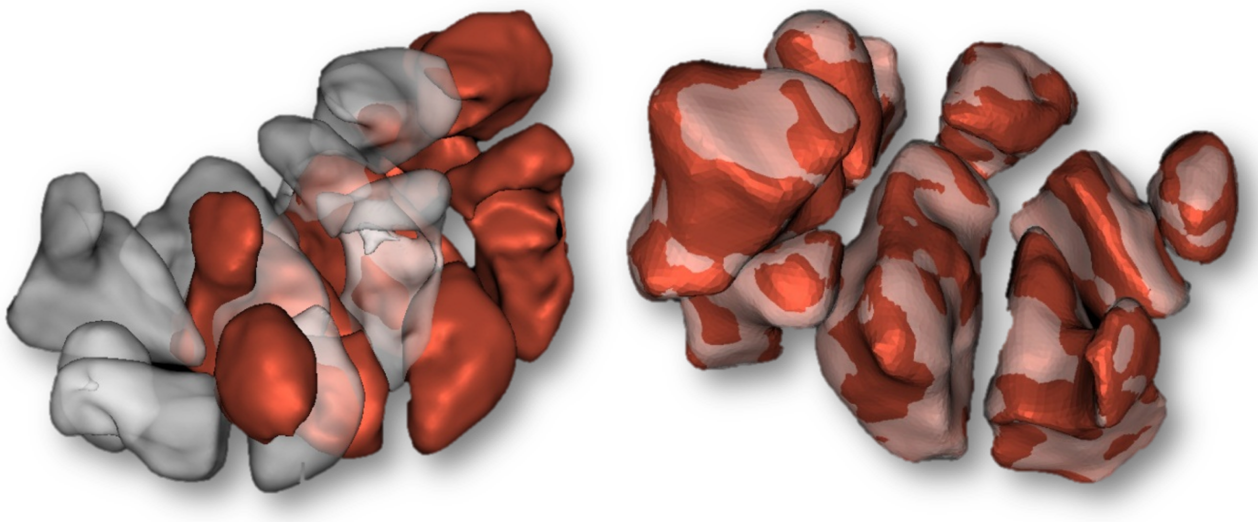


$$128 \times 128 \times 51$$

Our problem

- Two different but related co-registration problems
  - co-register a biomedical atlas with the MR images of a given patient;
  - co-register a temporal sequence of follow-up images of a given patient
    - the reference MR image is segmented;
    - the segmentation of the target image is unknown.

Our problem



Follow-up data **Co-registration**

Our problem

- We can apply a co-registration to
  - each couple of 2D image (single slices)
  - the input and target
    - 3D volume images (stack of 2D images)
    - 3D segmented surfaces (set of 3D surfaces)
  - …
- In the research session, we will focus on the co-registration of
  - couple of 2D images
  - volumetric images

Overall procedure

- Given a set of patient MR images, we select
  - the atlas from a single image or multiple raw images
    - segmented subparts & semantic labels by hand, by automated/semi-automated techniques;
  - follow-up data
    - not necessarily in the same reference frame
    - locally deformed by pathologies (eg., musculo-skeletal diseases, inflammation, etc)

Overall procedure

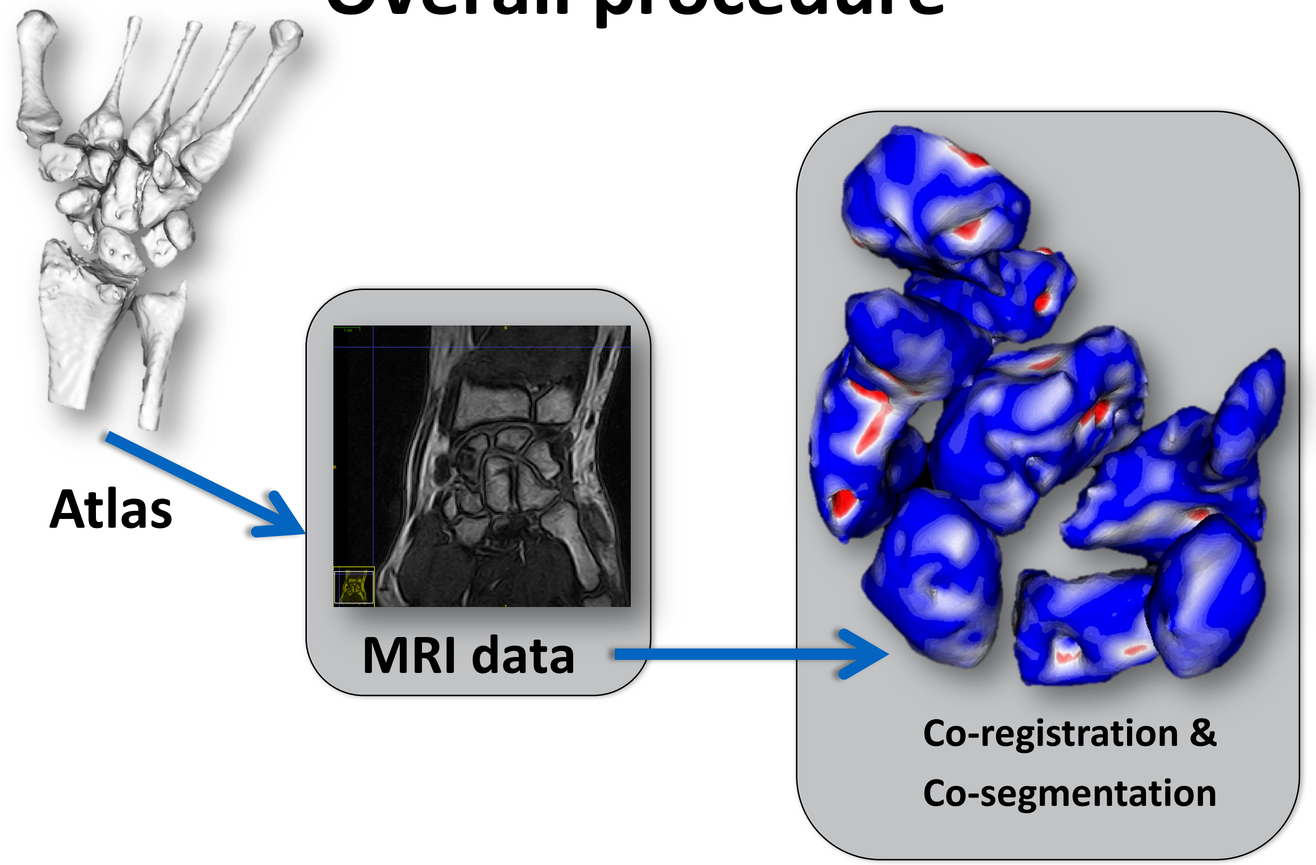
- segment the input image by performing a registration with a pre-segmented image (atlas-based segmentation);
  - the registration step yields a map from the atlas to the image to be segmented, which then inherits labels and segmentation;
  - the map allows us to obtain the labelling and segmentation (geometry&mesh) of the image;

Overall procedure

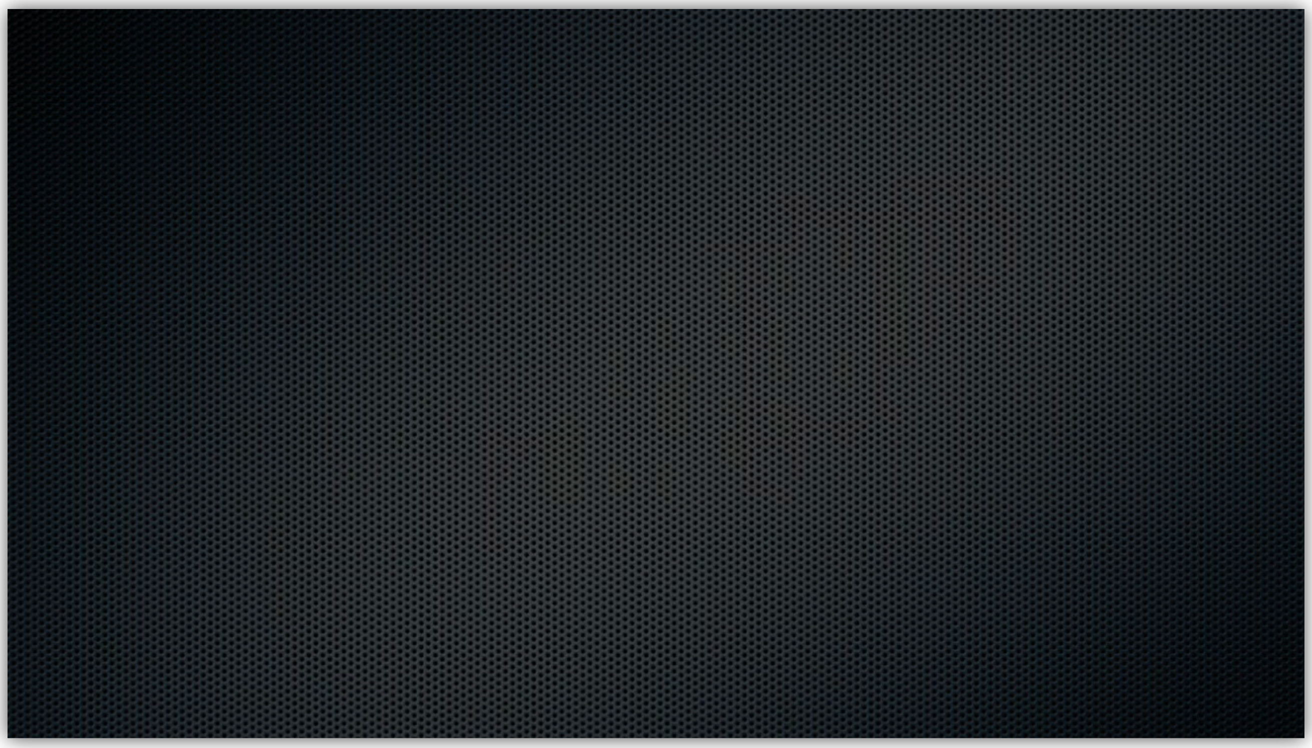
- the mapping must preserve the quality of the mesh;
- constructing the new, patient specific, geometry description and a good quality mesh of the patient;

- **Output**
  - mapping of the model structure onto the patient specific geometry
  - solving PDEs that describe a given phenomenon.

Overall procedure



Overall procedure - II



References

- See the Dropbox folders for papers
  - T. Rohlfing, R. Brandt, R. Menzel, D.B. Russakoff, and C.R. Maurer, Jr., *Quo vadis, Atlas Based segmentation, in J. Suri, D. L. Wilson*, and S. Laxminarayan (eds.), The Handbook of Medical Image Analysis: Segmentation and Registration Models, Kluwer, 2007
  - M.G. Albanesi, R. Amadeo, S. Bertoluzza, G. Maggi, *A new class of wavelet-based metrics for image similarity assessment*. Journal of Mathematical Imaging and Vision, Vol. 60, Issue 1, pp 109–127
  - G. Maggi Ph.D. Thesis
  - …

Project Details

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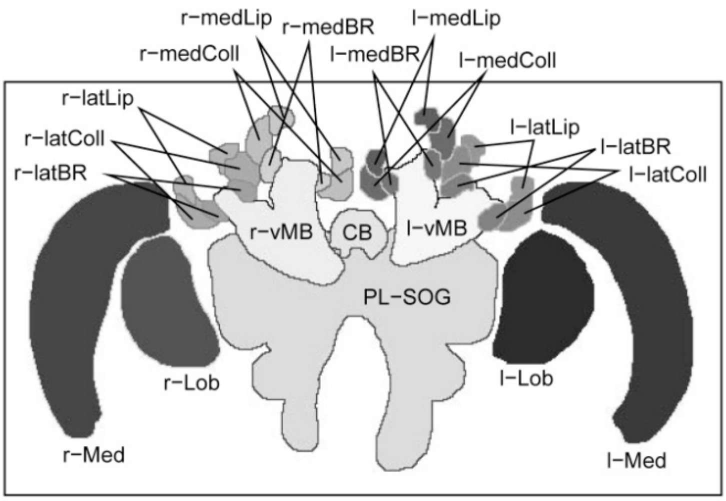
Outline

- Image & atlas-based segmentation
- Atlas selection
  - Single, variable, and multiple individual atlas
  - Single average atlas
- Image registration & trasformations
  - Non-rigid transformations
  - Parametric transformations
- Registration error: distance
- 2D examples

Image segmentation

- Segment an image = tag each pixel/voxel with a semantic label



- From the paper “Quo vadis, Atlas based segmentation” di T. Rohlfing, R. Brand, R. Menzel, D.B. Russakoff, C.R. Maurer jr

Image segmentation

- Intensity based classification
  - Group the gray level space in clusters
  - Each cluster is identified with a label
  - Each pixel is tagged with the label of the corresponding cluster

- Ok for classifying tissue types
- Bad when classifying anatomical structures

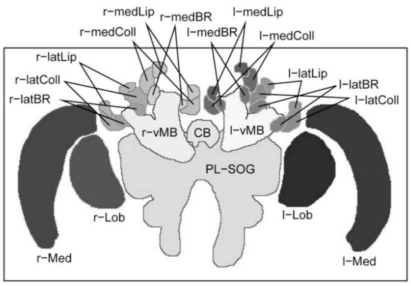
Image segmentation

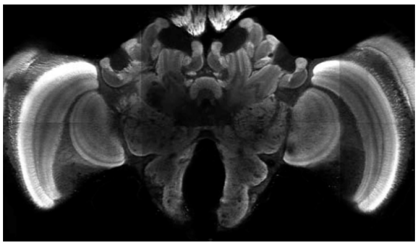
- Force the geometry of the image to evolve using
  - Image properties (gradient)
  - Constraints (smoothness of the segmented curves)

- Examples
  - Active contours (snakes) [Kass, Witkin & Terzopoulos ’87]
  - Level set method [Osher & Sethian ’88,Sethian ’99]
  - ...

Image segmentation

- Atlas-based segmentation: template image T, already segmented





- Find a map transforming the template image in the image R to be segmented
- “Tranfer” on R the segmentation of T

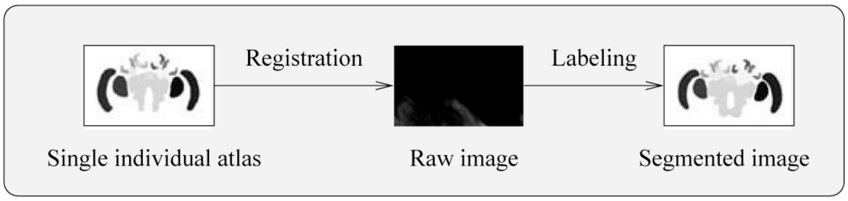
Atlas Selection

Atlas selection

- Choice of atlas has substantial impact on the result of the segmentation algorithm

- Four strategies
  - *Single atlas* for all images to be segmented
  - *Choice of best atlas* for each given image into an atlas set
  - *Average atlas* for all the images to be segmented
  - *Simultaneous use of multiple atlases*

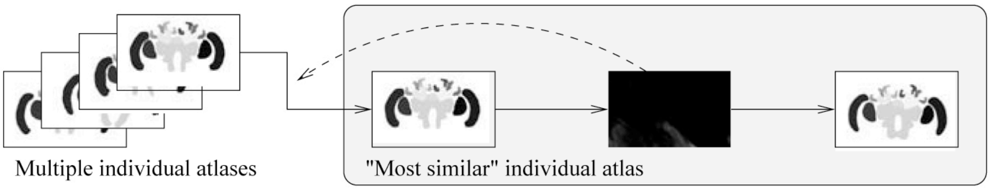
Single individual atlas



IND: Segmentation using a single individual atlas.

- Selection of an individual atlas
- Registration of all the raw images with the selected atlas
- (individual atlas = obtained by a single raw image)

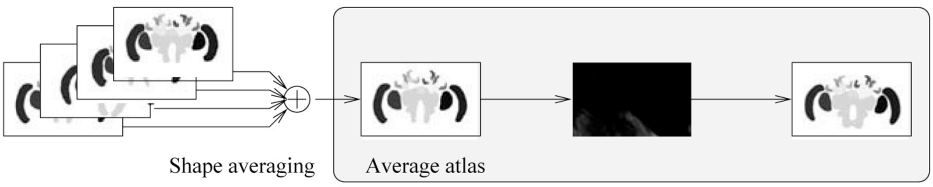
Variable individual atlas



SIM: Segmentation using the "most similar" individual atlas.

- Set of atlases
- Segment R using all atlases
- Select the atlas that gives the best risult
  - Maximum similarity
  - Minimum deformation

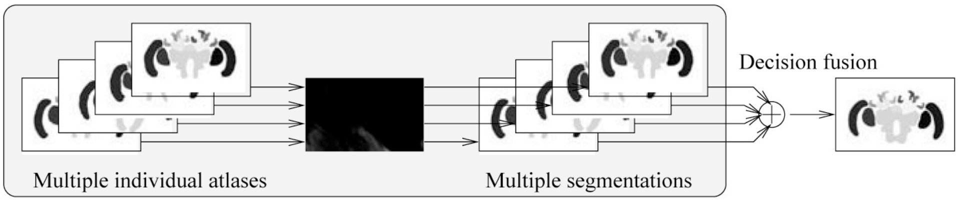
Single average atlas



AVG: Segmentation using an average shape atlas.

- Construct an artificial "tipical image" T from a set of images
- Construct corresponding atlas
- Register all images with T

Multiple individual atlas



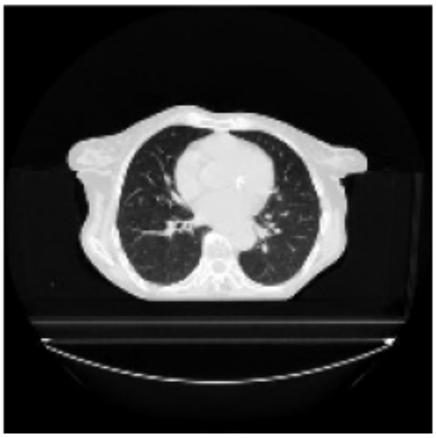
MUL: Independent segmentation using multiple individual atlases with decision

- Set of atlases
- Register R using each atlas
- Tag pixels with labels usin all information
  - Ex: voting strategy <-> tag with label chosen by highest number of atlases

Image Registration

Image registration

REFERENCE IMAGE **TEMPLATE IMAGE**



CT studies, of the same patient by different CT machines

Image registration

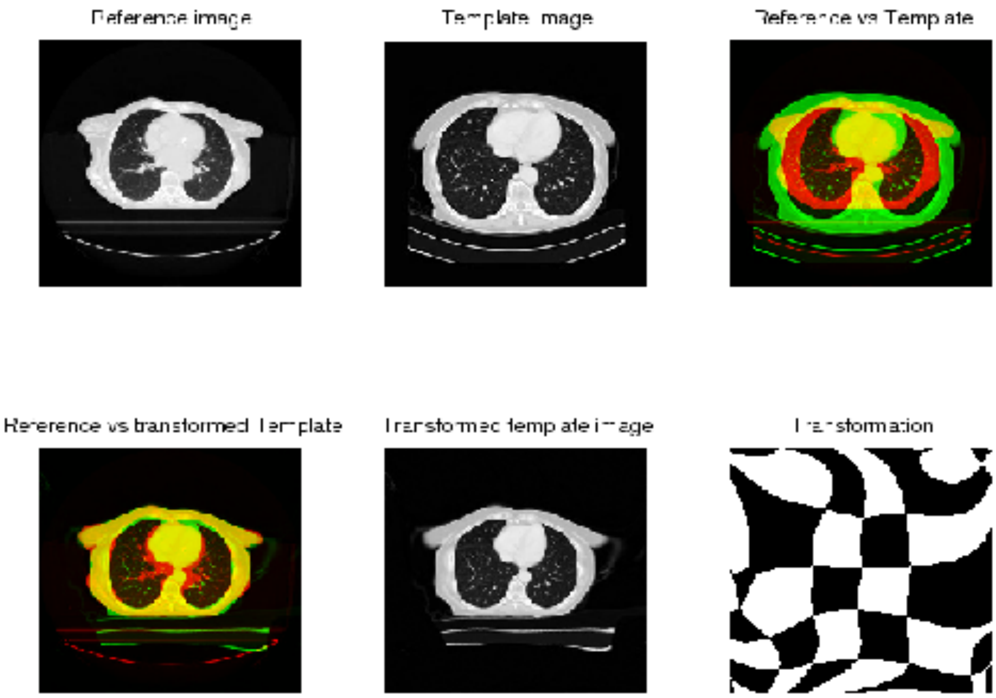


Image registration

- Grey scale images <-> real valued functions
- R: Ω_R -> $\mathbf{R}^+$, T: Ω -> $\mathbf{R}^+$

- Find mapping θ: Ω_R -> Ω such that $T \circ \theta$ and R are as "close" as possible

- Huge number of approaches
- Huge number of algorithms

See [Brown '92; Zitova,Flusser '03]

Image registration

- Huge number of algorithms obtained by combining
  - Different "distance" functionals
  - Different transformation classes
  - Different image models
  - Different optimization algorithms

- Huge number of possible combination

The transformations

- Rigid transformations (translations, rotations)
- Affine transformation

- Non rigid transformations
  - Splines, B-splines [Thevenaz, Unser '98]
  - Thin plate splines [Bookstein, '89]
  - Interpolating wavelets [S.B., G. Maggi '13]
  - ...
  - Parametric transformations

Parametric transformations

- N-dimensional parameter space
- Parameter α -> mapping θ_α

- (Ex: $\theta_\alpha = \sum \alpha_i e_i$)

- $\theta_\alpha = \Theta(x;\alpha)$
  - x : spatial coordinate (in $\mathbf{R}^2$)
  - α : parameter (in $\mathbf{R}^N$)
  - Θ : $\mathbf{R}^2 \times \mathbf{R}^N$ function (represents the selected class of transformations)

The "distance"

- **Im**: space of images
- d: **Im** x **Im** -> **R** functional measuring the discrepancy between the two images
- δ: **Im** -> **R** defined as δ(X) = d(X,R)
- c : $\mathbf{R}^N$ -> **R** cost functional
- $c(\alpha) = d(T^{\circ}\theta_{\alpha}, R) = \delta(T^{\circ}\theta_{\alpha})$

The "distance"

- Many different possibilities
  - Least square error
  - Human Visual System model distance [Mannos, '74]
  - Structural similarity index SSI [Wang et al, '04, Brunet, Vrscay, Wang '11]
  - Besov functional norm
  - Besov norm + divisive renormalization (generalised SSI) [S.B., G. Maggi, '14]
  - Mutual information [Viola, Wells '97; Thevenaz, Unser '98]
  - ...

The optimization problem

- Find α_0 in $\mathbf{R}^N$

$$\alpha_0 = \arg\min_\alpha c(\alpha)$$

- Unconstrained optimization problem

- Several possible optimization algorithms
- Choice depends on the characteristics of
  – Transformation
  – Distance functional

Image model

- Need rules to
  – Evaluate images out of their domain of definition (*extrapolation*)
  – Compute values of (deformed) images at pixels (*interpolation*)
  – Compute the values of derivative of images at pixels (*numerical differentiation*)

- Many different possibilities

Results

Reference image

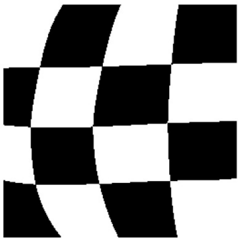
Template image

Reference vs Template

Reference vs transformed Template

Transformed template image

Transformation



<u>No noise</u>
Distance: LS

Results

Reference image

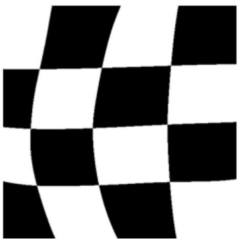
Template image

Reference vs Template

Reference vs transformed Template

Transformed template image

Transformation



<u>No noise</u>
Distance: SSIM
p=2

Results

Reference image

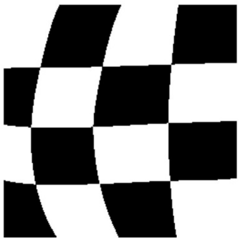
Template image

Reference vs Template

Reference vs transformed Template

Transformed template image

Transformation



<u>No noise</u>
Distance: GSSIM
p=2

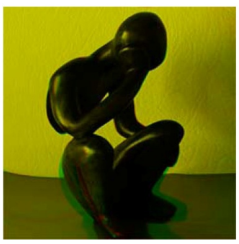
Results

Reference image

Template image

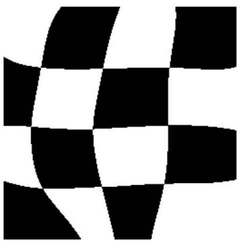
Reference vs Template

Reference vs transformed Template



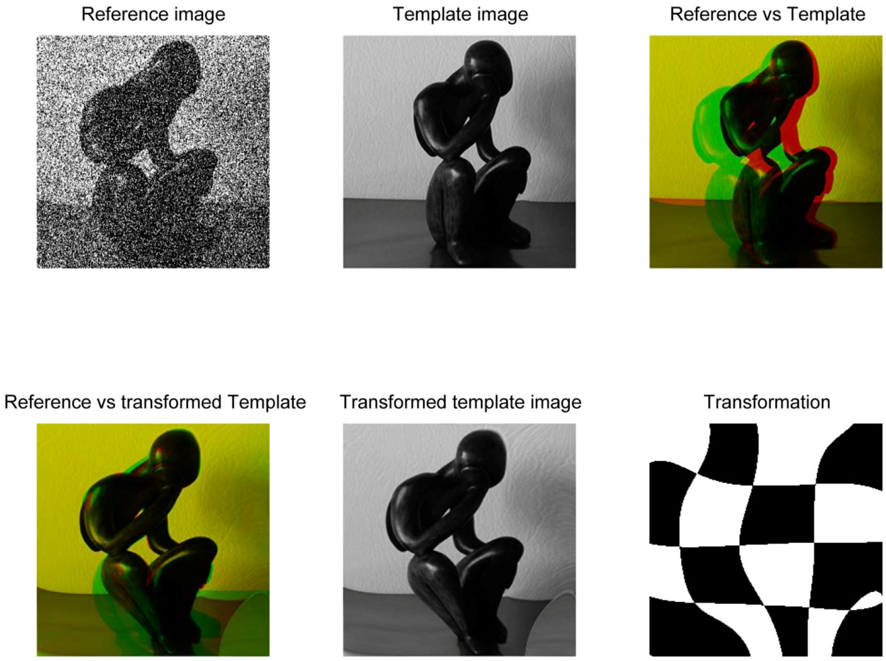
Transformed template image

Transformation



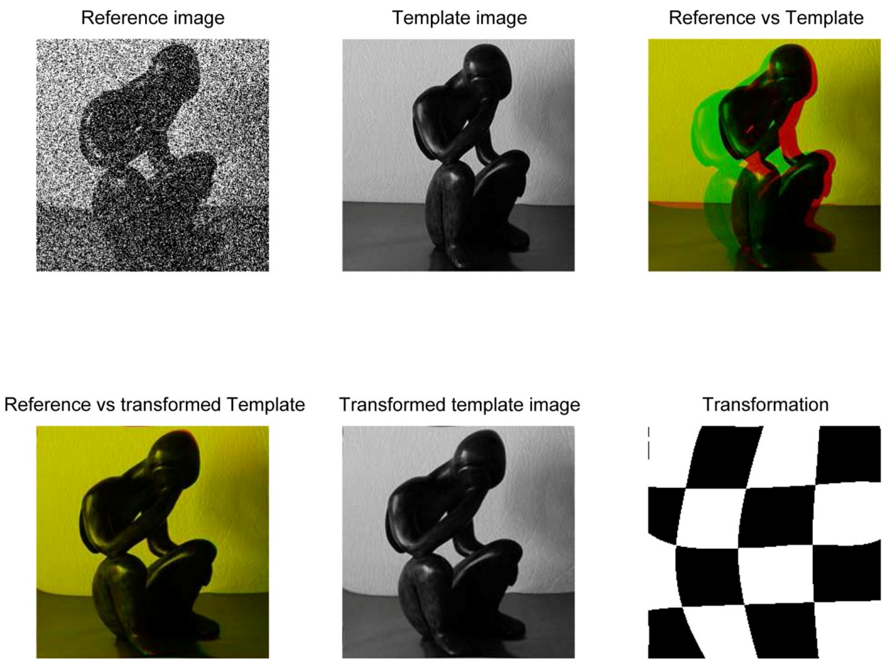
<u>Gaussian noise</u>
Distance: LS

Results



<u>Gaussian noise</u>
Distance: SSIM
p=2

Results



<u>Gaussian noise</u>
Distance: GSSIM
p=2

Lab Work

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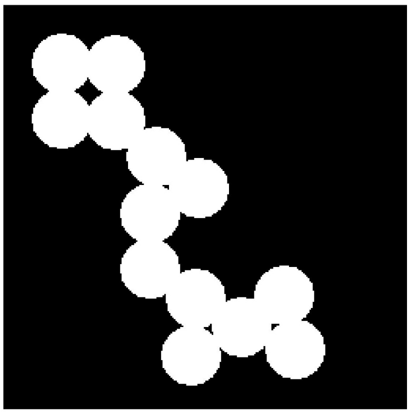
Overview

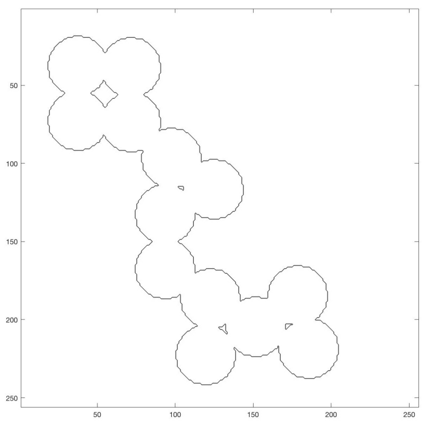
- **First week**
  - From 2D images to 2D meshes
  - Image/mesh transformation
  - Image/mesh Distortion evaluation
  - From 3D images to 3D volumetric meshes
  - …
- Next weeks
  - Image & mesh co-registration
  - Co-segmentation
  - …

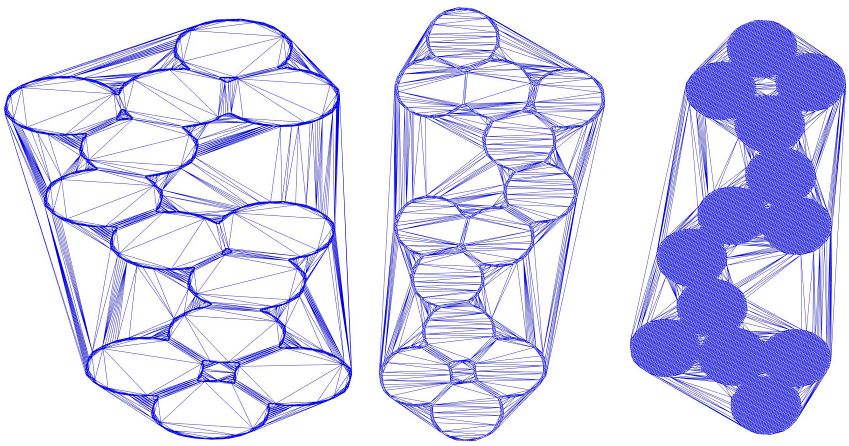
Day 1 & Day 2

- **2D Image processing**
  - Load a 2D image (toy example)
  - Extract the boundary components (black-white adjacent pixels): set of 2D pixels
  - Consider pixels as 2D points (with integer coordinates)
- **2D Mesh processing**
  - Generate a Delaunay triangulation of the input point set
  - Visualise the triangulation (vertices, edges, triangles)
  - Mesh data structures for mesh representation and visualisation
- **Discussion**
  - Delaunay triangulation
  - Different data structures for mesh representation
  - …

Day 1 & Day 2

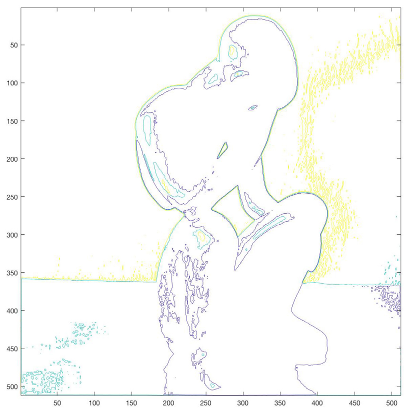


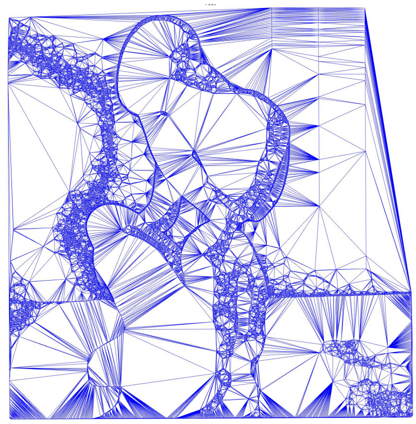




Triangle meshes with a different sampling density

Day 1 & Day 2



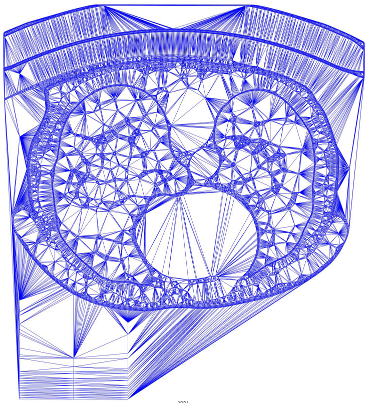


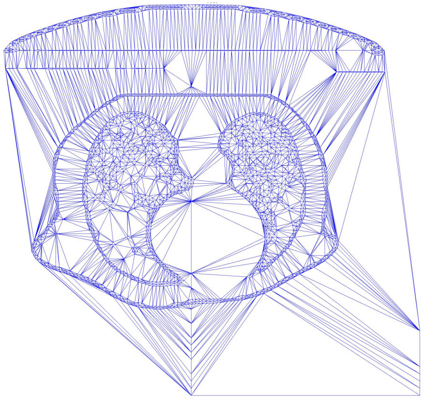
Colour images & complex 2D shapes

Day 1 & Day 2

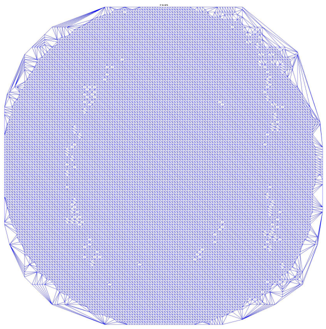
- **2D Mesh processing**
  - Change the sampling density of the Delaunay triangulation
  - Crop (if necessary) the Delaunay triangulation in order to fit the image size
  - Make the input image a square image
  - …
- **Discussion**
  - Strategies to handle the sampling densities
  - Main differences between 2D images & meshes
  - …

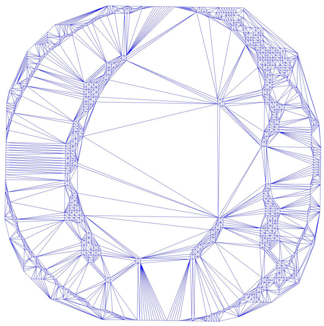
Day 1 & Day 2

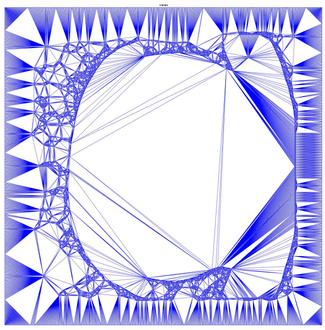




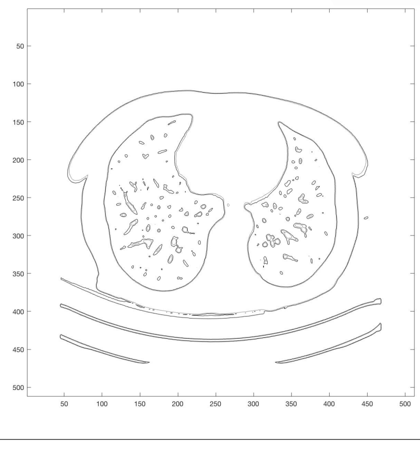
Different samplings &
Delaunay triangulations

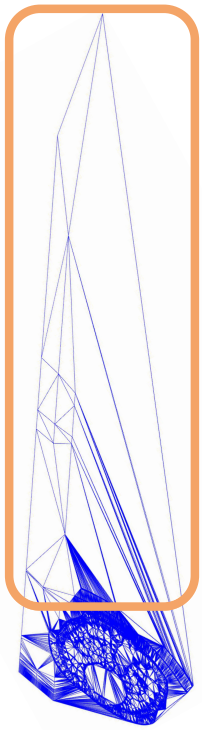


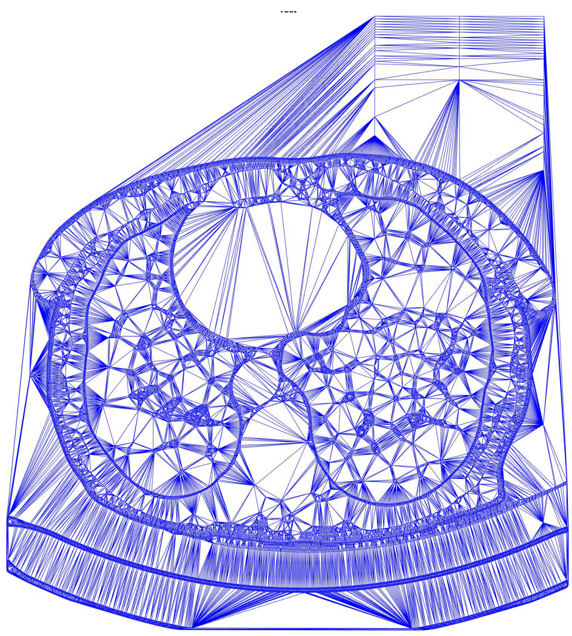




Day 1 & Day 2



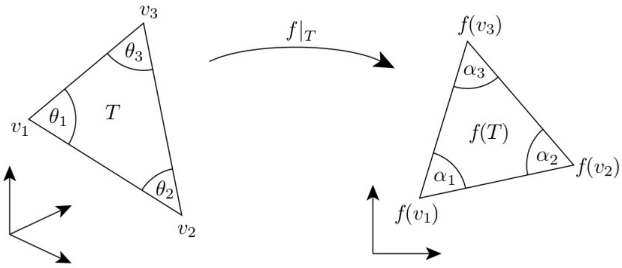




Crop Delaunay triangulation

Day 1 & Day 2

- **2D Mesh processing**
  - Compute and plot the main properties of the triangle mesh
    - Edge length
    - Angles
    - Triangle area
  - Handle triangle degeneracies



- **Discussion**
  - Mesh properties in terms of geometry & connectivity
  - Efficient computation of mesh properties
  - Mapping distortion & related metrics/applications
  - …

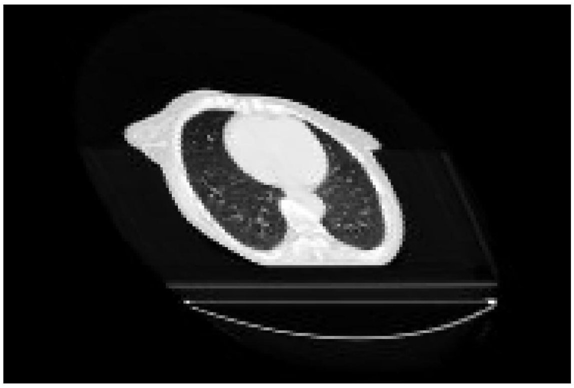
Day 2

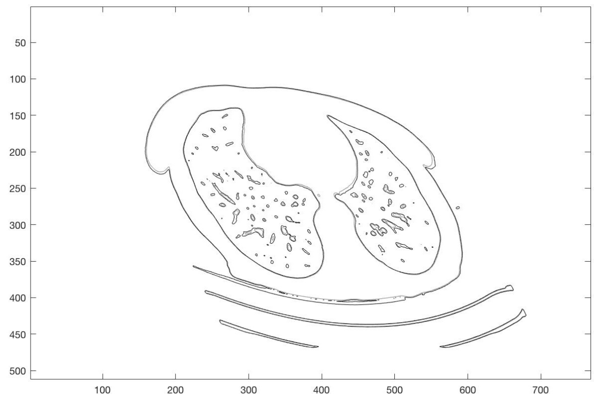
- **2D Remesh**
  - **Goal:** define "equivalent" representations of a given mesh
    - eg., up-to a given accuracy and/or according to a set of optimality constraints
  - **Criteria:** uniform sampling density, feature preservation, guarantee on min-max angles of triangles (eg., for FEMs)
  - **Tools:** MeshLab
  - **Tests:** remesh the surfaces that we have generated in the previous examples by
    - optimizing 1 or more of the previous criteria (or other criteria→Meshlab routines for remeshing)
    - adding geometric noise to the input data

Day 3

- Applying a **transformation** to the input image
  - Compute the image deformation
  - Generate a 2D mesh of the input and deformed images
- Analyse the **2D mesh distortion** in terms of
  - Edge length (*isometry-preserving*)
  - Triangle area (*area-preserving*)
  - Triangle angle (*conformal*)
- **Discussion**
  - Image&mesh distortion
  - Bounds to the image/mesh distortion
  - …

Day 3

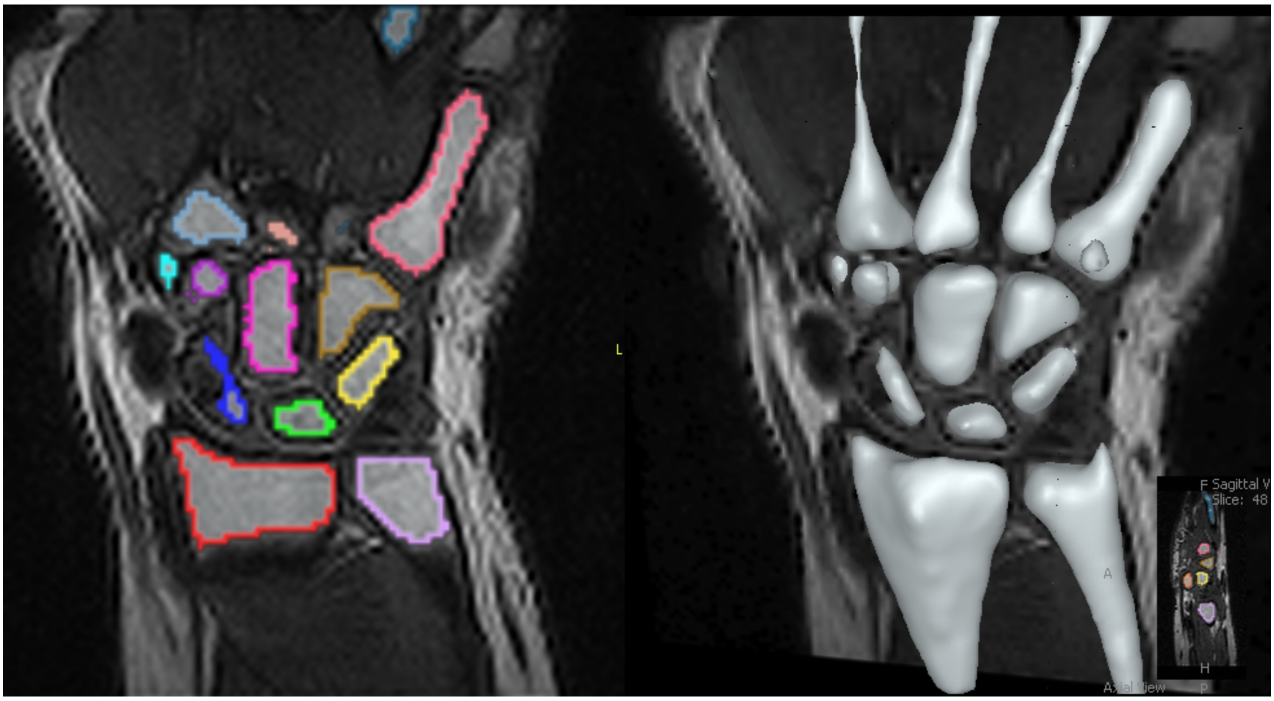




Day 4 & 5

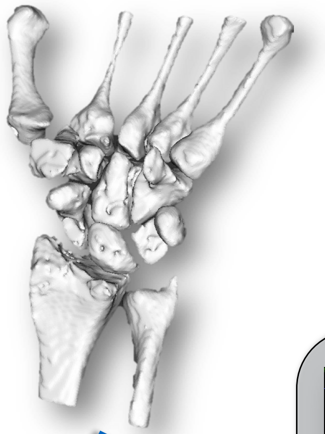
- **3D Image & mesh processing**
  - Load a MRI data set and its deformation
  - Visualize the stack of 2D images
  - For each 2D image
    - Make the input image a square image
    - Compute the deformation
    - Evaluate the deformation distortion as 2D image and triangle mesh
  - Compute the distortion of the whole stack and discuss the results (eg, with respect to a different image crop/extension)

Day 4 & 5

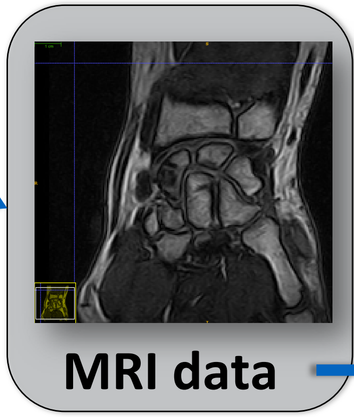


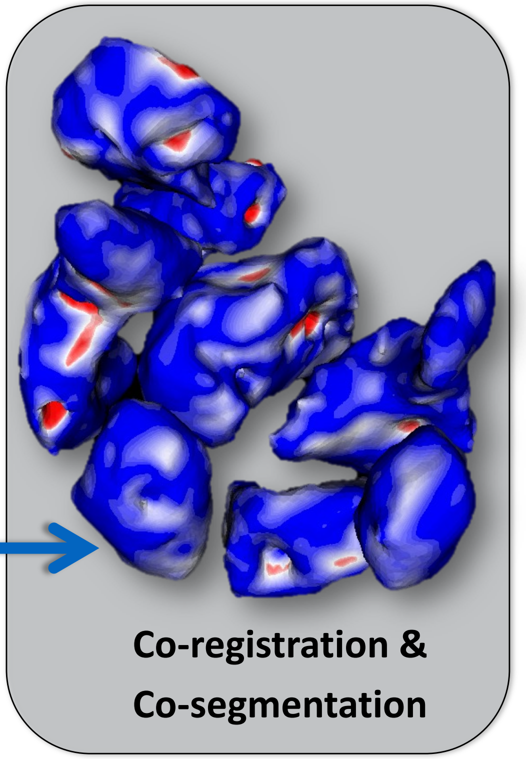
$$128 \times 128 \times 51$$

Day 4 & 5



“Meta”-
segmentation





Day 4 & 5

- Construct a 3D Delaunay triangulation
- Visualise MRI data & segmented 3D data
- …

Next steps

- For questions, I'll be available by
  - Email: patane@ge.imati.cnr.it
  - Skype: giuseppe-imati
- Next weeks
  - Silvia Bertoluzza
  - Micol Pennacchio