A novel and accurate approach for non-rigid registration is proposed. New feature descriptors are built as voxel signatures using scale space theory. The global motion of the imaged object is modeled by matching these descriptors. Local deformations are modeled through an evolution process of equi-spaced closed surfaces (iso-surfaces) which are generated using fast marching level sets and are matched using the built feature descriptors. Performance validation using the finite element method (F.E.M.).
What is image Registration?

It is the process of spatially aligning two or more images so point-by-point correspondences can be established between them.

Points corresponding to the same anatomical point are mapped to each other.

\[ T(X) = T_{global}(X) + T_{local}(X) \]
Global Alignment

First task consists in building invariant feature descriptors which will be matched to find the correspondent pairs of control points.

- This stage involves three main steps:
  - Interest Points Detection: Scale Space Theory is used to detect the most stable features w.r.t. scale changes.
  - Descriptor Building using gradient orientations histogram.
  - Feature Matching and Estimation of the global transformation:
    
    \[
    T_{global}(x, y, z) = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \\ z \end{pmatrix} + \begin{pmatrix} a_{14} \\ a_{24} \\ a_{34} \end{pmatrix} \]

The Structure of the 3D feature Descriptor
Local Alignment

- Iso-surface evolved in target image to match those of source image in **four** steps
  - Generate the distance map inside of the imaged organ (object of interest)
  - Use this distance map to generate iso-surfaces
    - Number to be set by user
    - Not necessarily the same for both volumes
  - Find Correspondences between iso-surfaces
  - Evolve iso-surfaces in volume A to match those in volume B
Our evolution approach

\[ \phi_{n_{iso}}^A (.,k) : \text{Iso-surface on target volume} \]

\[ \phi_{m_{iso}}^B (.,k) : \text{Iso-surface on target volume} \]

\[ S(h, \gamma_h) : \text{Euclidean Distance between two corresponding iso-surface points} \]

\[ S_{niso,niso-1}^A(h) : \text{Euclidean Distance between two corresponding iso-surface points} \]

\[
V(h) : \begin{cases} 
= 0, & \text{if } S(h, \gamma_h) = 0 \\
\leq \min[S(h, \gamma_h), S_{niso,niso-1}(h), S_{niso+1,niso}(h)], & \text{otherwise} 
\end{cases}
\]  

\[ V(h) = \exp(\beta(h).S(h, \gamma_h)) - 1 \]
Surface Evolution Scenario

\[ S(h, \gamma_h) \]

\[ S^A_{niso+1, niso}(h) \]

\[ S^A_{niso+1, niso}(h) \]
2D and 3D applications
Validation using F.E.M.

- Image variation is modeled as a mechanical response
  - Create a F.E. model of the imaged organ
  - Instantiate the model on a test image
  - Pick and simulate a deformation
  - Apply the simulated displacement field to produce a deformed image
  - Register the original and deformed images
  - Compare the recovered voxel displacements to the bio-mechanically simulated ones.
3D Model Construction

Application to Brain MRIs:

Brain Tissue Segmentation (FSL)

Mesh Generation (TetSplit)

Mechanical Parameters Assignment

B.C.’s and Loads Definitions

Three Deformations are Simulated:
- 2x Gravity Induced Deformations (L.E. & Ogden H.E.)
- Ventricles Contraction

F.E. Solving (Abaqus)
Deformed Images Generation

- Deformed images are generated by F.E. interpolations

- For each simulation case:
  - Compute the dense displacement within each element $el$

$$u(x, y, z) = \sum_{j=1}^{4} H_j^e(x, y, z)u_j^e$$

- shape functions
- simulated nodal displacements
Before Registration

Rigid Alignment

Own-FFD Elastic Registration

Our Elastic Registration

http://www.cvip.uofl.edu

09/01/06
Quantitative assessment of the registration accuracy. Comparison with our own implementation of the (FFD), for the three simulated cases. Displacements correspond to the simulated ones.

<table>
<thead>
<tr>
<th></th>
<th>Max. Displacement (mm)</th>
<th>Mean Displacement ± std. dev. (mm)</th>
<th>Max Error (mm)</th>
<th>Mean Error± std. dev. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Our Method</td>
<td>FFD</td>
</tr>
<tr>
<td>Case 1</td>
<td>9.88</td>
<td>6.08 ± 1.06</td>
<td>2.08</td>
<td>9.18</td>
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<tr>
<td>Case 2</td>
<td>4.76</td>
<td>2.25 ± 0.68</td>
<td>2.36</td>
<td>7.46</td>
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<tr>
<td>Case 3</td>
<td>1.68</td>
<td>0.55 ± 0.38</td>
<td>0.63</td>
<td>4.03</td>
</tr>
</tbody>
</table>

http://www.cvip.uofl.edu
Red: Abaqus  Green: Ours  Blue: OWN-FFD
Conclusions

- A new approach for 3D Deformable Registration was proposed
  - Scale space and curve evolution theory based.

- Proposed a Validation framework based on FEM

- Outperforms our own implementation of the B-spline based FFD technique

- Quantitative and Qualitative assessments are promising