Elastic registration of medical images using finite element meshes

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Summary. In this paper a new method for elastic registration of medical images is presented. The method uses corresponding regions of gray values, which are segmented interactively. The deformation part is based on finite element meshes generated from the segmented regions. During the deformation process, the similarity between the deformed mesh and the target image is measured and the 'intensity' of the deformation is controlled.

Keywords: Mesh generation, deformable model, elastic matching

1 Introduction

The registration of volumetric medical images obtained from different imaging devices, e.g. from CT and MRT, is an important task for neurosurgery and radiotherapy. In order to achieve better accuracy, the registration has to be a non-rigid one, because MR images can be geometrically distorted up to 5 mm [1].

Strongly related with the problem of distortion is the so called atlas-matching problem, where the patient data set has to be registered with an electronic atlas. Again, non-rigid registration is necessary to individualize the electronic atlas and to obtain sufficient accuracy.

2 Principle approach

Therefore, we developed a new method for deforming medical images, which is based on finite element meshes. For simplicity, we assume that one image remains rigid, while the other image has to be warped toward the rigid one. In the following context, the rigid image will be defined as $R(x)$ and the image that will be deformed as $T(x)$. Our approach can be divided into the following four parts:

1. Both images are divided into N corresponding regions. As a result, we obtain a set of regions R_i and T_i (i = 1..N) which represent three-dimensional domains. Since R_i and T_i are corresponding domains, our goal is to deform T_i, so that it becomes R_i.

2. For performing the deformation, the regions T_i are transformed into a finite element mesh, which serves as a deformable model.
3. The generated model is warped towards the rigid image *R(x)*. In the first warping step, high similarity is achieved. In the second relaxation step, the 'strength' of the deformation is reduced. Warping and relaxation steps are performed several times to obtain high similarity with low 'amount' of deformation.
4. The deformed model is transformed into a volumetric image by resampling the generated mesh. To avoid aliasing an oversampling is performed.

3 Segmentation of corresponding regions

For finding corresponding segments, region growing is a useful approach. The image can be segmented by placing a 'seed' point within the interior of a homogeneous region and 'growing' out to the grayscale-bounded and connected border of that region. It should be noticed that the segmented regions do not have to represent anatomic structures. It must only be guaranteed, that the segmented regions R_i and T_i are corresponding in a certain way.

If the two images *R(x)* and *T(x)* are of the same modality, defining corresponding regions is easy, cause the thresholds of the gray values of two corresponding regions are the same in both images. Figure 1 illustrates the result of the seed-point segmentation. The images show one slice of a series of MR-scans of a patient lying in two different positions (right, left). The cross-hair indicates the position of a seed-point. The colored areas show the two segmented regions. Corresponding regions have been segmented with the same thresholds and seed-points. Obviously, they do not represent any existing anatomic structure.

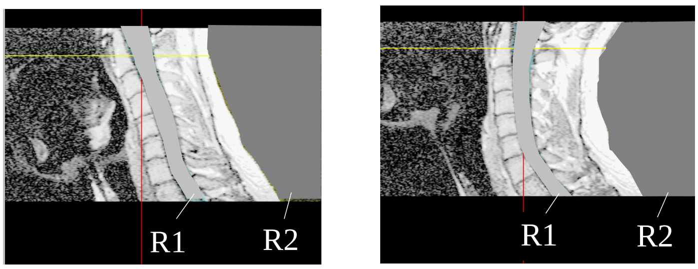

Fig. 1: Two MR images of the same patient lying in different positions.

4 Generating deformable models

1. Since the volumetric image is divided into different homogenous regions, each of this regions will be replaced by a finite element mesh consisting of tetrahedral elements. For mesh generation [2], a set of points lying on the surface of the regions is created, which is then triangulated with by the Delaunay triangulation. With a classification step, the obtained tetrahedras a classified corre-

sponding to the segmented regions. Figure 2, left, presents the obtained set of points from the regions of shown in Figure 1. Figure 2, middle, presents reduced set of contour points and Figure 2, right, shows the obtained classified sets of tetrahedras.

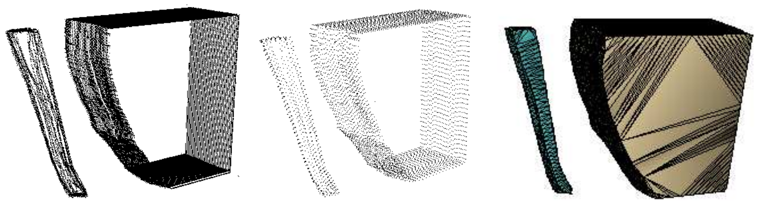

Fig. 2: The generated set of points (left) is reduced (middle) and triangulated (right).

5 Deforming meshes

With the mesh generation, the voxel based representation of the template image *T(x)* is transformed into a tetrahedral based representation. This tetrahedral based representation is now deformed towards the rigid image *R(x)*. Therefore, the nodes n_i of the mesh have to be moved towards a specified direction. For simplicity, we assume that both images *T(x)* and *R(x)* are globally aligned and equally scaled.

Since R_i and T_i are corresponding regions and each node of the mesh lies on the surface of a region T_i, its new position has to be somewhere on the surface S_i of the region R_i. Additionally, we assume that taking the shortest line between the actual position of a node and its target surface is an intelligent guess for determining the displacement vector of a node. But calculating the shortest line between each node and its target surface is very time consuming. Therefore, we use the concept of the distance transformation [3], which serves as a potential field. Each node is attracted by the potential field D_i of its target surface S_i. Figure 3 presents the distance maps of the two segmented regions R_1 and R_2.

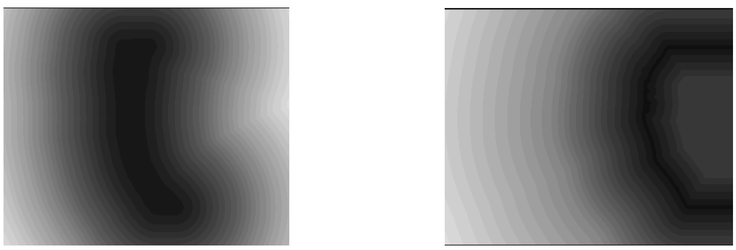

Fig.3: The distance map of the segmented regions R_1 (left) and R_2 (right).

5.1 Forward warping

After the surface S_i and its distance transformation $D_i(x)$ have been calculated for each region R_i, the iterative deformation process can be carried out: For each node *n*, its position $p(n)$ in the distance map is determined. Since the negative gradient $g_i(n) = -grad\ D_i\ (p(n))$ represents a vector with a direction towards the surface S_i, this direction is a good estimation for the direction of the displacement vector. The length of the vector can be estimated directly form the distance map, since an entry $d_i(n)$ in the map represents the length of the shortest line between its position and the surface.

However, the influence of only one region R_i has been considered yet, but normally one node is part of two or more regions. Therefore, the influence of the different regions has to be taken in account. Since there is no region which is more important than the others, the average of the displacement vectors of all different regions is taken. The mean square distance m_i of all nodes in D_i is taken as a similarity measurement concerning the region R_i. The maximum of all mean square distances over all different regions $a = max(\ m_i\ )$ is the criterion for aborting the iteration process.

5.2 Relaxation

Even if matches with high accuracy can be obtained with the straight forward warping approach, the question for measuring the 'mass' of deformation still remains open. To measure a deformation, we have to introduce some methods of the theory of elastic deformations.

As the displacement at each point x inside a tetrahedra T is know through the displacement vectors of the nodes (we assume a linear form function), we are now able to evaluate the distortion tensor $v_{ij}(\mathrm{x})$ inside T. Cause geometric interpretation of $v_{ij}(\mathrm{x})$ is very complex, it is helpful to determine the eigenvectors a_i and eigenvalues e_i of v_{ij} which are called principal axes a_i and principal extensions e_i of the medium T at x. With the help of the principal extensions, we determine the relative change k_i of length along the principal axes a_i ($k_i = sqrt(1+2e_i)$).

With the help of the values k_i , we are able to derive a measurement for the 'mass' of a deformation: The quantity q of the deformation is minimal if no deformation occurred ($k_i = 1$) and the quantity increases the more k_i differs from one. Therefore, a rough estimation of the quantity of the deformation of a tetrahedra can obtained with $q_T = \mathrm{abs}(\ 1 - 1/k_i\ )$: The lowest quantity is $q_T = 0$ and the highrt the quantity the bigger becomes q_T. Then the 'mass' q_m of the total deformation can be estimated by sum of the quantity values of each tetrahedra.

In order to reduce the 'mass' of the deformation, we now expand the compressed tetrahedras and compress the expanded. Therefore, we determine the three vectors rv_i with the direction equal to that of the three principal axis a_i. If the tetrahedra is compressed ($k_i < 1$), the vector points away from the center of gravity g_T of the tetrahedra, otherwise it points towards g_T. Then, the nodes of the tetrahedra are moved into the direction of the vectors rv_i and the deformation of the tetrahedra is reduced.

This 'relaxation displacement vector' is calculated for each node of a tetrahedra. Since one node shares multiple tetrahedras the resultant displacement vector $d(n)$ of node n is obtained by averaging over the displacement vectors $d_T(n)$ of all tetrahedras T of the mesh which belong to node n.

6 Resampling of volumetric images

After the mesh *M* has been deformed, a deformed volumetric image *T'(x)* has to be generated. First, the size of the target image *T'* has to be defined. In order to avoid undersampling in regions of compression, the resolution of the target image *T'* should be higher than the one of the original image *T*. However, if the compression is too large, two or more gray values have to be stored in one single voxel. Then the average gray value of them is taken. At regions of decompression, a tri-linear interpolation of the original gray-values can be used to obtain smooth results. Figure 3 shows the re-sampled image *T'(x)* (left) and the target image *R(x)* (right).

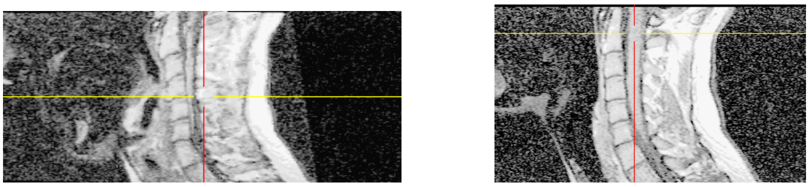

Fig. 3: The deformed image *T'(x)* (left) and its target image *R(x)* (right).

7 Summary

We presented a method of deforming volumetric images based on finite element meshes. Two main procedures have been introduced: the warping step and the relaxation step. With alternating use of these two steps, an elastic matching of two images can be obtained. The use of meshes relieves the problem of finding corresponding structures, since corresponding regions can be segmented with less interaction.

8 Acknowledgment

This research was performed at the Institute of Real-Time Computer Systems and Robotics, Prof. Dr.-Ing. U. Rembold, Prof. Dr.-Ing. H. Wörn, Prof. Dr.-Ing. R. Dillmann, Faculty of Computer Science, University of Karlsruhe, Germany. The work is being funded by the 'Sonderforschungsbereich Informationstechnik in der Medizin - Rechner- und sensorgestütze Chirurgie' of the Deutsche Forschungsgemeinschaft.

9 References

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