Intraoperative Registration on Standard PC Graphics Hardware

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Abstract. Movements of brain tissue limit the accuracy of preoperative medical images in the intraoperative situation. In this work we address non-rigid registration of MR images of the brain, compensating for *brain shift* effect and thus improving surgical procedures. We approximate 3D non-linear deformations with a piecewise linear model in order to align the pre- and intraoperative data. Significant acceleration is achieved by making substantial use of the features of modern graphics cards on standard PCs. The method has been validated in 21 clinical cases and has shown numerous advantages. No extraction of anatomical landmarks is needed for this registration algorithm. Another advantage is universality, since no expensive specialized hardware is required. The algorithm can be executed on a standard PC equipped with one of the graphics cards providing 3D texture mapping.

1 Problem and Medical Background

One of the fundamental problems in computer assisted neurosurgery is the intraoperative deformation of the brain, referred to as the brain shift phenomenon. This deformation is related to the resection of tissue and leakage of cerebrospinal fluid. As the preoperative functional data loses its validity during proceeding surgery, an intraoperative update of this data must be performed. Thus the non-linear transformation between pre- and intraoperative MR data needs to be determined and subsequently applied to the preoperative fMRI data, which provides the surgeon with the exact anatomical information.

In the literature there exist several registration approaches based on the identification of different anatomical or fiducial features [1,2]. A practical application, however, necessitates a more automatic and flexible strategy. Hence, our main interest is focused on voxel-based methods, as already investigated in [3,4]. Registration of medical data is a complex and time consuming process. For this purpose a strategy based on expensive and specialized hardware can be used, as introduced in [5,6]. With regard to the application in clinical routine, a universal, fast and reliable method is desirable. Due to this, an approach is suggested that uses standard PC graphics hardware in order to perform voxel-based hardware accelerated alignment of pre- and intraoperative MR data. The thus obtained alignment can then be used to accomplish an intraoperative update of fMRI data within the operating room.

2 Methods

In order to compensate for tissue deformations during brain surgery a non-linear registration of medical image data is needed. In the presented approach two datasets are considered, one of them remains unchanged (fixed dataset) during the whole optimization procedure. The other dataset (floating dataset) is transformed until an optimal alignment of both image data has been found. The procedure ends when a chosen similarity measure between these two datasets reaches its maximum. For this purpose mutual information was applied. As an optimization method, Powell's direction set algorithm was chosen.

To make use of modern PC graphics hardware we model the distortion of soft brain tissue with a hierarchical, piecewise linear transformation with extensive use of hardware accelerated 3D texture mapping. In order to accelerate all trilinear interpolation operations the floating dataset is loaded into 3D texture memory. For the calculation of the similarity measure, the transformed floating dataset has to be interpolated in the grid of the fixed dataset in each optimization step. This is a very time consuming procedure if performed in software exclusively. In contrast to that, the presented method uses trilinear interpolation capabilities of standard PC graphics hardware for the purpose of considerable acceleration. This is achieved by slicing the floating dataset into planar polygons, which consist of several linear patches. The image information corresponding to these polygons is then efficiently interpolated in 3D texture memory.

Another acceleration was to be obtained by using OpenGL functions enabling to compute 1D histograms in graphics hardware. This hardware feature is used in a special manner, suggested in [6], in order to obtain the 2D histogram. The related joint probability distribution is a prerequisite for the computation of mutual information between the reference and the floating dataset. However, the flexibility of our approach allows applying any histogram-based similarity measure.

At the beginning of the registration a regular grid is associated with the floating dataset which is adaptively refined during the registration procedure. Thereby the image volume is subdivided into a certain number of patches. The boundary vertices of this piecewise linear grid are fixed. During the optimization process the best alignment is determined by finding the optimal positions of the free inner grid vertices. There is a unique correspondence between the grid and the 3D texture image. A change in the grid structure changes the shape of the corresponding inner linear patches, which simultaneously changes the mapping of the associated 3D texture. Intuitively this refers to the deformation of the respective dataset.

There are regions, like in the vicinity of the resected tumor, where the occurring deformation is more significant than in other parts of the brain. Considering this fact, adaptive subdivision is applied in order to improve the precision of the registration algorithm. For this purpose additional inner vertices are added if a patch is marked for further refinement. At the same time the adaptive approach accelerates the optimization procedure, since only parts of the whole volume have to be subdivided.

3 Results

We have validated our method in 21 surgical cases, where a brain tumor was removed during a surgery and brain shift had occurred. In 16 out of 21 cases a rigid registration was performed. In the remaining 5 cases non-linear registration was additionaly applied in order to make a time comparison between these two fusion strategies. Throughout our experiments we used pre- and intraoperative T1-weighted MR data with an image matrix of 256 $\times$ 256 pixels and 112 - 128 slices. The registration was performed on a PC (AMD Athlon, 1.2 GHz) equipped with a GeForce3 graphics card providing 64 MB of 3D texture memory. The evaluation showed that the developed approach can be used in the operating theater, as the times that we achieved are very close to real time. For a rigid transformation the average computation time was 30 seconds. By the non-linear registration for a volume initially subdivided into $4 \times 4 \times 4$ piecewise linear patches, the time required for the total registration was about 11 minutes on average, which was possible due to the effective exploitation of trilinear interpolation capabilities of the GeForce3 graphics card. Moreover, a visual inspection using methods of direct volume rendering confirmed the very good accuracy of the non-linear registration results. A comparison between the rigid and the non-linear registration is shown in Figure 1.

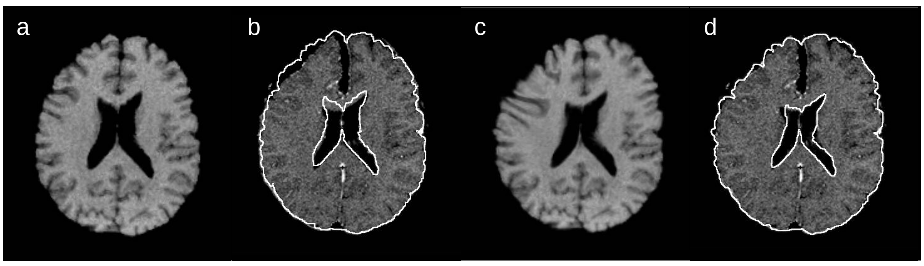

Fig. 1. Rigid and non-linear registration applied to MR images of the brain. a) Slice image at the beginning of the surgery. b) The corresponding rigidly registered slice of intraoperative scan overlayed with the contours of initial scan. c) Non-linearly deformed image a). d) Slice of intraoperative image overlayed with the contours of deformed image

In addition, we have recently experimented with the registration of downsampled data. This can be efficiently computed in hardware by applying rendering in a reduced viewport. This technique improved the overall computation time to about 4 minutes for the non-linear case. We also observed that the quality of the registration was not affected by the smaller render viewport. Moreover, there were cases, where the accuracy of the achieved registration was higher with downscaled data. It seems that this can be explained with a lower sensitivity to artifacts included in the MR scans after resampling. It decreases the probability of stucking in a local maximum during the optimization procedure. However, there is a need to analyze this modification more intensively.

4 Discussion and Conclusion

In this paper we propose an approach for non-linear voxel-based registration of pre- and intraoperative medical image data. We compensate for brain shift, applying adaptive subdivision of the MR image volume into piecewise linear patches, which enables the description of complex, non-linear deformations of the soft tissue. The method showed very good accuracy and at the same time high performance. It is also generally applicable, since standard PC graphics hardware was used. Both low computation times and high precision enable this method to be applied in the intraoperative field.

We concentrated on the intraoperative use of our method, so registration of monomodal data was considered. This approach can also be applied in order to fuse data of different modalities, such as CT and MR, due to the robustness of the histogram-based similarity measures.

Our future research is concentrating on better and faster optimization methods because optimization appears to be one of the most significant time limiting factors in the registration process. The influence of a reduced viewport on the precision of the computed transformation is going to be the subject of further investigations as well.

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