Analysis and Visualization of the Brain Shift Phenomenon in Neurosurgery

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Abstract. In this paper we present a method for analyzing the brain shift. The brain shift is a brain deformation phenomenon, that occurs during surgical operations on the opened head. This deformation makes navigation within the brain very difficult for the surgeon, as preoperative magnetic resonance images invalidate very quickly after the beginning of the operation. Up to now not enough is known about this deformation phenomenon in order to come up with solutions for corrective action. The aim of the tool which is presented here is to prepare ground for a better understanding by visualizing the deformation between two 3D brain data sets, where one has been taken preoperatively and the second one during the operation after the brain shift has occured. We propose a new method for the modeling of the deformation by means of efficient distance determination of two deformable surface approximations. Color coding and semi-transparent overlay of the surfaces provides qualitative and quantitative information about the brain shift. The provided insight may lead to a prediction method in future.

1 Introduction

The comprehensive diagnosis of diseases and lesions is considerably assisted by different tomographic imaging modalities like CT *(Computed Tomography)* and MRI *(Magnetic Resonance Imaging)*, since they provide various information and improve the spatial understanding of anatomical structures. Integrating such data into an operation with a target in the center of the brain makes the access easier and tremendously reduces the risk of hitting critical structures. Due to the rigid behavior of the skull it is possible to define a reliable transformation between the image data and the head of the patient in the beginning of an operation using a neuro-navigation system. Thereby, showing the position of an instrument in relation to the image data, it is intended to predict structures which are approached. However, depending on the drainage of cerebrospinal fluid and the movement or removal of tissue, the initial shape of the brain changes and leads to the brain shift phenomenon which results in great inaccuracies during the ongoing course of the operation [4]. Therefore, it is important to understand the correlation of all effects and to correct the shift of the brain. Data sets showing the head of the patient before and after the shift of the brain represent an important prerequisite of the analysis. Currently, they are mainly obtained with magnetic resonance scanners [3] or to a more limited range with ultrasound devices [2].

In order to gain some qualitative and possibly quantitative insight into the brain shift phenomenon we have implemented a tool, that is capable of visualizing the difference of a brain in a pre- and intra-operative stage. The main problem that is encountered in this assignment, is the fact, that the brains to be analyzed are not necessarily registered. The registration and the brain shift problem are coupled as it is not possible to compute an appropriate registration function, without knowing which parts of the data set are influenced by the brain-shift.

The analysis and visualization of this phenomenon is surface based. The surfaces are extracted from the two datasets separately, using the deformable surface approach presented by Lürig et al. [5]. This technique approximates boundary structures in the data set. In contrast to the original work on deformable surfaces of Terzopoulos [7] the presented approach does not require a certain surface topology. The two separately generated surfaces are then fused into a single visualization. First the two surfaces are registered in this fusing approach. This is done in two steps. The first step is a manual rigid registration. The second step the final registration is done by a variation of the ICP (iterated closest point) algorithm of Besl et al. [1]. Special considerations will be made to account for the brain shift distortion in the solution presented here, as this phenomenon may severly falsify the registration. The final visualization is based on the minimal distance of a point to the other surface. This distance is used for coloring and absolute measuring of the brain surfaces by assigning color values to the vertices of the surfaces.

The next section will give a detailed explanation of some of the details of this method. Section 3 finally gives some visualization examples including some interpretations and statements on the medical relevance of this method.

2 Visualization of the Brain Shift

The previous chapter has introduced the overall work-flow to generate the brain shift visualization. The main stages of this process, which are surface generation, registration, distance computing and visualization are explained in further detail in this chapter.

Surface generation is done by an iterative process which requires a coarse initial surface. The initial surface is modeled using a tool, that is based on Delaunay tetrahedrization. First a few surface vertices are specified in a slicing view. Then these vertices are connected using this tetrahedrization method. Non-convex parts of the object to be segmented may be modeled by interactive deletion of some of the tetrahedra. The resulting surface is the boundary surface of the tetrahedral complex which is then fed into the deformable surface module.

The deformable surface technique refines this initial triangular mesh to generate a refined hull, that describes the boundary of the brain. The transformation of the surface is formulated as a minimization problem, that reduces the curvature of the surface and its size and tries to push the surface into regions of high gradient magnitude. If the volume to be analyzed is described by a function $f : R^3 \to R$, and the surface to be generated by $\mathbf{v} : \Omega \subset R^2 \to R^3$, then the surface $\mathbf{v}$ has to minimize the following functional [7]

$$\int_\Omega \sum_{i=1}^{3} \Big(\tau (\nabla \mathbf{v}^{(i)})^2 + (1-\tau)((\Delta \mathbf{v}^{(i)})^2 - 2H(\mathbf{v}^{(i)})) \Big) + P(\mathbf{v})\, dA \to 0, \qquad (1)$$

where $\mathbf{v}^{(i)}$ denotes the i-th component of $\mathbf{v}$, $H(\mathbf{v}^{(i)})$ the determinant of the Hessian Matrix of $\mathbf{v}^{(i)}$. The external energy term P is defined as

$$P(\mathbf{v}) = -(w_{edge} \, \|\nabla (G_\sigma * f(\mathbf{v}))\| + w_{image} f(\mathbf{v})) \,, \qquad (2)$$

where G_σ denotes a Gaussian kernel with variance σ. This functional is minimized using a multi-level finite difference solver.

This procedure is applied to both data sets generating an approximating surface of the pre-operative and the intra-operative brain respectively. These two surfaces have then to be compared. In order to perform a visualization with measuring of distances, the two surfaces have to be registered in advance. This is done using a variation of the ICP algorithm [1]. To compute the transformation, which registers data set A with data set B, for every vertex of the data set A the nearest vertex in the data set B with respect to the Euclidean norm has to be found. The ICP algorithm minimizes the procrustean distance. The procrustean distance between two surfaces is the average value of the distances between the mentioned pairs of vertices. Using the estimated correspondences a least squares fit is applied, that computes the affine transformation between the two point sets. The fit is performed using a singular value decomposition from the Numerical Recipies [6].

The problem however is, that the least squares fit procedure has to account for the brain shift in order to avoid the compensation of this phenomenon. Our approach avoids this problem by excluding the vertices from the registration function, that are influenced by the brain shift. The user has the possibility to define these vertices by interactively specifying a maximum distance for the vertices to be considered. The problem however is, that this method only works, if the brain distortion of the surface is of larger magnitude than the registration error, that has to be compensated. As this is not the case in most situations, an additional manual rigid preregistration has been implemented.

In order to visualize the brain shift, we would like to annotate every vertex of one brain surface with the distance it has moved away from the other surface. The reasonable assumption, that is made here, is that every point on one of the brain surfaces corresponds to its nearest point on the other surface. If x is a point on one surface and Y is the other surface to which we have to compute the distance, we have to determine $d(x, Y) = \min_{y \in Y} ||x - y||_2$. In order to calculate this distance we would have to compute the smallest distance of the regarded vertex to each of the triangles, which is quite expensive. As the surface under discussion is also just an approximation with limited accuracy and relatively small triangles, only its vertices are considered to compute the distance. In this way the relationships between the vertices, which have been computed for the ICP registration, can be used directly to estimate the distance to every vertex.

The resulting values are used to color-code the registered surfaces. Either the whole distance value spectrum is mapped to different colors ranging from blue to red, or a threshold is visualized using two colors. It appeared to be useful to draw one brain surface colorized and the second one in a transparent way. This technique provides a good visual impression of the brain shift.

3 Results

We have applied the brain shift analysis tool to two data sets acquired pre- and intra-operatively from a Magnetom Open in the neurosurgical operating room of the University clinic Erlangen. For illustration purposes a volume rendering of the first brain is shown in a pre-operative stage in image 1(a) and in an intra-operative stage in image 1(b).

The first brain is shown in image 1(c) and 1(d). The two generated surfaces consist of 4061 and 5344 triangles. The time needed to compute the correspondences and to perform one step in the ICP algorithm lasted 7 seconds on a R10000 175MHz O2. The second brain, which has undergone a lateral approach is displayed in images 1(e) and 1(f). These two surfaces consist of 28928 and 30080 triangles. The needed computational time was three minutes in this case. Both brains are visualized using a color spectrum and a threshold visualization each.

The method of surface-based visualization of brain shift gives a quick overview and impression of the localization and extent of brain shift. In case of surgery with a slightly elevated head in the supine position as is shown in images 1(c) and 1(d). In this position the patient is lying on its back side. It is used for lesions in the frontal and fronto-parietal region, the main brain shift, amounting up to 1.5 to 2 cm, is localized in the frontal lobes, so that by drainage of cerebrospinal fluid and tumor removal the frontal lobe just follows gravity and moves to a great extent. In the case of a lateral approach the brain moves accordingly to the midline, also following gravity (see Fig. 1(e)). Additionally this method enables evaluation of the extent of brain shift at the borders, especially at the deepest point of a tumor, a crucial landmark during surgery, to know whether to continue with resection, or to encounter the risk of damaging vital brain areas. To allow this the tumor has to be segmented in the preoperative images and then these have to be compared to the pictures where the main tumor volume is already removed (see Fig 1(f)).

This visualization method emphasizes the problem of brain shift during neurosurgical procedures, which may result in great inaccuracies of neuro-navigation in the ongoing course of an operation due to leakage of cerebrospinal fluid, tumor removal and the usage of brain spatulas. The need for a correction of brain shift to allow further accurate neuronavigation, can be satisfied by the large scale approach of performing intraoperative magnetic resonance imaging which allows an update of neuro-navigation, thus compensating brain shift. It could also be achieved by predicting the brain deformation by some simple intraoperative distance measurements with the help of a navigation system which in combination of the knowledge of the extent and behavior of brain shift allows a recalculation of neuro-navigation which takes this deformation into account.

4 Conclusion and Future Work

After a brief discussion of the brain shift phenomenon in general, we have introduced a tool, that is capable of visualizing this phenomenon by comparing two extracted surfaces of different 3D images. These visualizations allow for first quantitative statements.

The next steps in visualization and evaluation of the extent of brain shift will be a combination of the demonstrated method with methods based on volumetric approach, to allow further descriptions of the brain shift phenomenon in the future, which will may be then enable us to perform a recalculation of neuronavigation, thus compensating for the brain shift.

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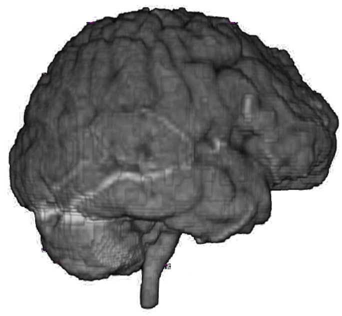
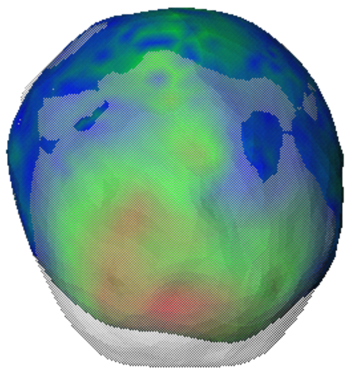
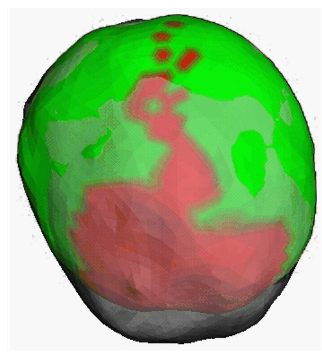
(a) Brain preoperative



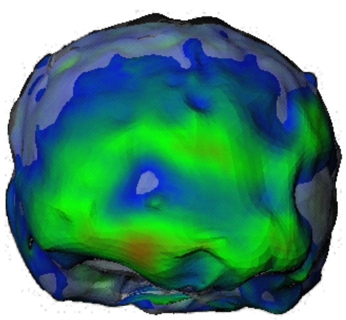
(b) Brain intraoperative



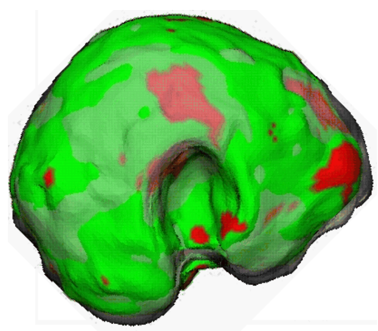
(c) maximum shift value 1.6 cm



(d) threshold 5 mm



(e) maximum shift value 1.4 cm



(f) threshold 3 mm

Fig. 1. Examples for the brain shift visualization