Robust Nonrigid Registration to Capture Brain Shift from Intraoperative MRI

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Intraoperative MRI

OBJECTIVE:

The intraoperative magnetic resonance imaging system allows neurosurgeons to acquire images of the brain during the neurosurgical procedure. In the case of brain tumor resection, this system helps to follow the deformation of the brain (see figure 1 for an example of the intraoperative brain shift). However, even if it provides significantly more information than any other intraoperative imaging system, it is not clinically possible to acquire full diffusion tensor, functional MR or high resolution MR images in a reasonable time during the procedure. Ideally the intraoperative image would in fact be used to precisely measure the brain deformation. This transformation could then be used to update the set of pre-operative images to provide the surgeon with substantial information for the upcoming of the procedure. Ultimately, the full registration process should be automatic, robust to image outliers and may only represent a fraction of the MR image acquisition time (less than a minute).

METHODS:

We developed a patient-specific registration algorithm to measure intraoperative deformation of the brain. A sparse displacement field D is estimate in a first step with a weighted block matching algorithm computed on information-based selected points. Each measured displacement is associated with a confidence in the measure provided by the coefficient of correlation between the two matching blocks. We rely on a patient-specific finite element model of the brain to ensure a realistic deformation. With this physics based approach, we introduce *a-priori* knowledge in the relative stiffness of the intra-cranial structures (brain parenchyma, ventricles, skull, falx cerebri...).

In the literature, the registration problem is often posed as an energy minimization problem, in our case:

$$W = \underbrace{U^T K U}_{Mechanical\ energy} + \underbrace{(HU - D)^T S (HU - D)}_{Matching\ energy} \quad (1)$$

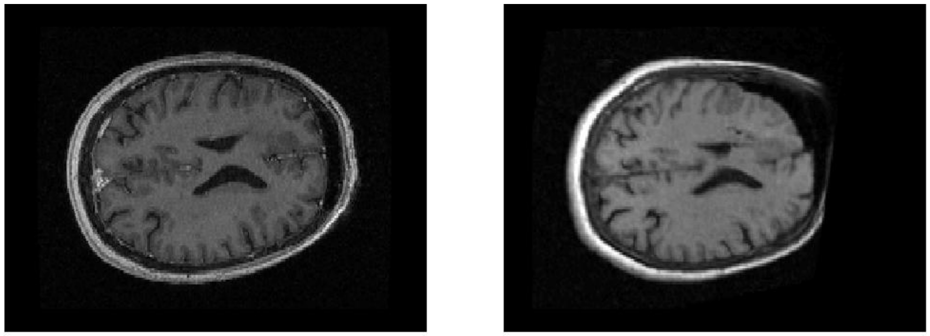

Fig. 1. Left : preoperative MR image. Right: intraoperative image of the same axial slice, rigidly registered on the preoperative image.

with:

- U the mesh vertices displacements vector.
- K the mesh stiffness matrix.
- D the measured displacements vector.
- H the linear interpolation matrix inside the tetrahedra (notice that $HU-D$ defines the displacement error).
- S the matching stiffness taking into account the confidence in each matching.

This approximation formulation however suffers from a systematic error: the final displacement of the brain mesh is a trade-off between the pre-operative rest position and the measured positions so that the deformed structures never reach the measured displacement.

One could then think at the registration problem as an interpolation problem, finding the mesh vertices displacements U so that

$$HU = D \tag{2}$$

The algorithm to solve equation 2 under the constraint of mechanical energy $W = U^T KU$ is formalized through the Lagrange multipliers $\tilde{F}$. The new energy $\tilde{W}$ now also depends on the Lagrange multipliers:

$$\tilde{W} = U^T KU + \tilde{F}^T (HU - D) \tag{3}$$

Classically we obtain the optimal displacement and force, by writing that $\frac{\partial \tilde{W}}{\partial U}$ and $\frac{\partial \tilde{W}}{\partial \tilde{F}}$. One then obtain:

$$\begin{bmatrix} K & H^T \\ H & 0 \end{bmatrix} \begin{bmatrix} U \\ \tilde{F} \end{bmatrix} = \begin{bmatrix} 0 \\ D \end{bmatrix} \tag{4}$$

However, the block matching algorithm outputs a noisy estimate of the displacements that could not be used for direct interpolation formulation.

Therefore we developed a new approach which takes advantage of both formulations to iteratively estimate the deformation from the approximation to the interpolation based formulation while rejecting outliers at each iteration. This gradual convergence to the interpolation solution is achieved through the use of an external force F_i applied on the mesh at each iteration i which balance the mesh internal mechanical energy $U_i K U_i$. The robust outliers rejection step is based on the least trimmed squared algorithm, coupled with a linear cost function:

$$F(D_k) = \alpha \left\| R_k (D_k - {U_k}^S) \right\| + \beta \tag{5}$$

where R_k represents the tensor of structure for block k defined in the preoperative image at position I_k by $\frac{\mathbf{1} * (\nabla I_k)(\nabla I_k)^T}{trace(\mathbf{1} * (\nabla I_k)(\nabla I_k)^T)}$. With such a cost function, the rejection criterion is more flexible with points that account for larger displacements. The overall algorithm can then be synthesized by the following scheme:

$$\begin{array}{rcl} F_i & = & K U_i \\ \left[K + H^T S_i H \right] U_{i+1} & = & H^T S_i D_i + F_i \\ \text{Reject block k} & \backslash & \{F(D_k) > 0\} \\ \text{Compute } H^T S_{i+1} H & \text{and} & H^T S_{i+1} D_{i+1} \end{array}$$

In this way the mechanical energy of the brain is used to compute a physically realistic deformation based on the estimated displacements. At each iteration step toward the interpolation, we reject a fraction of the measured displacements based on their error with respect to the current deformation estimate. This gradual transformation estimation makes our algorithm both robust to outliers and accurate with respect to the remaining displacements.

RESULTS:

In order to meet the clinical time constraints, we parallelized the expensive block matching part of the algorithm. We could thus achieve a registration in less that 45 seconds on an heterogeneous group of 15 PCs, composed of 3 dual Pentium IV 3Ghz, 3 dual Pentium IV 2Ghz and 9 dual Pentium III 1Ghz.

We successfully tested our algorithm on 6 cases of brain tumor resection performed in the 0,5 T open magnet system (Signa SP, GE Medical Systems) of the Brigham and Women's Hospital. Figure 2 shows an example of the registration results for the first patient of our database, corresponding to the previous figure 1. The results for all the 6 cases can be seen on a dedicated web page[1].

Compared to other fast registration techniques, it is to our knowledge the first method using the full volumetric image information and proposing an alternative to the classical approximation and interpolation formulations. In addition, since the method does not rely on the brain surface to perform the registration, it does not depend on the quality of the pre or intra-operative brain segmentation.

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[1] http://www-sop.inria.fr/epidaure/personnel/Olivier.Clatz/registration/results/

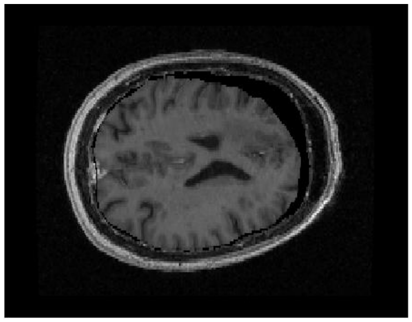 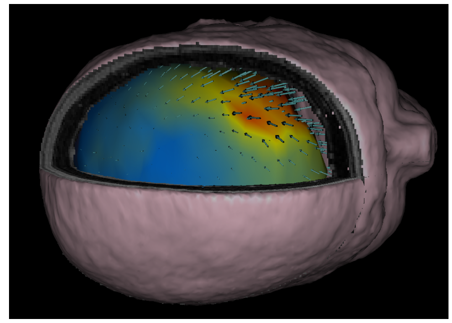

Fig. 2. Left : preoperative MR image registered on the intraoperative image. Right: 3D view of the brain deformation

CONCLUSION:

We proposed a new approach to estimate the intraoperative deformations of the brain. The registration computation time makes it clinically viable for the update of preoperative images during the procedure. The progressive transformation estimation combined with the outliers rejection step makes it robust up to 50% of bad measures. Regarding the results obtained on the 6 patient dataset, this algorithm seems to meet the high accuracy needed for a neurosurgical procedure.

In the future, we wish to investigate a way to fuse the power of the algorithm with the expert knowledge of the surgeon to guide the algorithm in its extensive displacement research.

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