



A New Automated Method for Three-Dimensional Registration of Medical Images¹

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Abstract

A new technique for three-dimensional image registration was developed and tested using T1 and T2 weighted Magnetic Resonance image studies of the head. The method uses the fuzzy c-means classification algorithm for outlining the surface contours and then minimizes iteratively the mean squared value of the voxel per voxel weighted ratio of the two trilinearly interpolated cubic voxel volumes. A total of 200 two-dimensional and 240 three-dimensional registration experiments were performed and showed that the method is signal intensity independent, it has registration accuracy better than 1 degree for rotations and 1 voxel for translations and it is not affected by the deterioration in the imaging resolution for voxel sizes up to 1.8 mms.

1. Introduction

Medical imaging modalities (Computed Tomography, Magnetic Resonance, Positron Emission Tomography, Single Photon Emission Computed Tomography) provide information that illustrates human brain anatomy and function. This information is often complementary and its correlative use can improve diagnostic accuracy. For example, the merging of fine anatomic detail from MR images of the brain with functional PET images allows the measurement of regional cerebral function[6]. Likewise, MR and CT images describe complementary morphologic features. Bone calcifications are seen

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best on CT images, while soft tissue structures are differentiated better by MR[5].

Medical image registration is the procedure of geometrically aligning two image volumes so that voxels representing the same anatomical structure may be superimposed one on another[4]. Registration techniques make it possible to superimpose features from one image study over those of another image study from a different modality. These techniques can also be applied to studies of the same modality taken at different times so that point-by-point arithmetic operations such as image averaging, subtraction and correlation can be performed[1].

In recent years there has been a rapid growth of neurological applications of medical image registration with applications that address both diagnosis and therapy. Registration is progressively playing a larger role in image interpretation in many different procedures.

Several methods for medical image registration have been proposed[4,5]. There are device-based methods and feature-based methods. The device-based methods use head-holding devices that keep the patient's head at a fixed orientation and/or external fiducial markers visible in both image sets. The fiducial marker coordinates are used to estimate the geometric transformation that establishes a one-to-one mapping between the two image spaces. These methods are non-automated, technically demanding and require a significant amount of effort at the time of each scan. Furthermore they have been found to be less accurate than feature-based techniques.

Feature-based methods use the anatomic information inherent in the two image sets. These techniques follow a general methodology with four steps[5]:

- a) extraction of features in each image
- b) pairing of these features
- c) choice of geometric transformation and estimation of its parameters
- d) application of this transformation.

Feature-based techniques do not require any special procedures or devices at imaging time and may be applied retrospectively. The extraction of the anatomic features can be performed either manually with the assistance of an expert user or automatically.

The purpose of this paper is to present the application of a new automated, feature-based method of medical image registration to the solution of the problem of three-dimensional registration of MR images of the head.

2. Methods

To register two three-dimensional studies, the method uses the following processing steps:

1) Each of the scans of the two studies is classified with the use of the fuzzy c-means classification algorithm as presented by Bezdek et al. [7]. Three clusters are used and a threshold for each scan is computed by taking the mean value of the centers of the two lowest clusters. This threshold is the value that separates the signal from the background area for each scan. The

lowest of all the thresholds computed for each study is considered the global threshold for this study. No thresholding operation is performed at this point.

II) The two studies are interpolated using a trilinear interpolation routine to create the cubic voxel volumes. This step is necessary because of the different resolution in the xy plane and the z axis used in the acquisition of three-dimensional medical image data.

III) All the voxel values of the two volumes are compared to the global thresholds. Voxels that have signal intensities lower than the corresponding global threshold are set to zero.

IV) Finally, an iteration loop based on Chebyshev's approximation theory[9] is used to minimize the registration function, which is defined as the mean squared value of the average weighted ratio $\tilde{R}$ of the two volumes:

$$E(\tilde{R}^2) \quad \text{with} \quad \tilde{R} = \frac{1}{2} * \left(\text{weighted}\left(\frac{A}{B}\right) + \text{weighted}\left(\frac{B}{A}\right) \right)$$

where A and B are the two volumes. The ratios of the two volumes are computed on a voxel per voxel basis and weighting is performed by setting the voxel ratios with background voxels in the denominator to a standard high value. All the other voxel ratios are not affected and generally have low values.

A block diagram of the registration method is shown in figure 1. Figure 2 illustrates the application of the fuzzy c-means classification method to an MR scan.

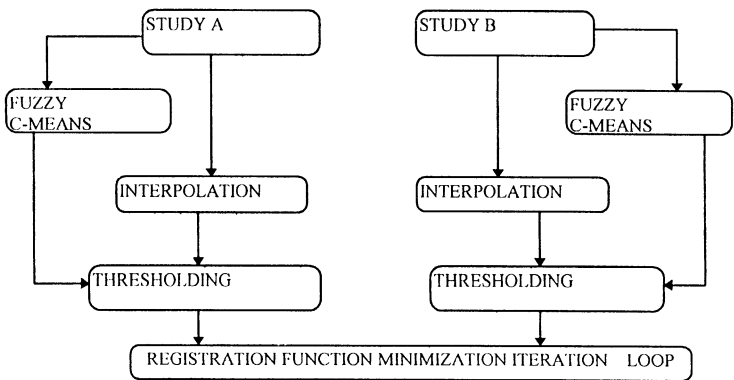


Figure 1: Block-diagram of the registration method.

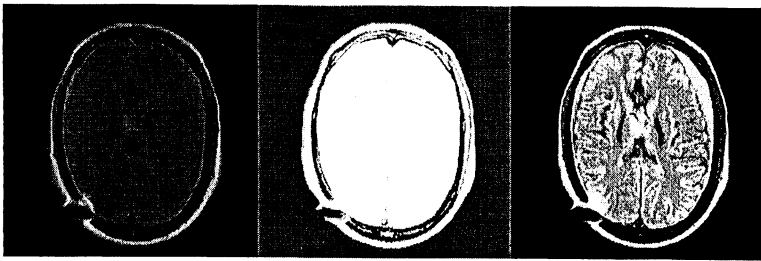


Figure 2: Application of the fuzzy c-means to an MR scan. Left: the original scan. Center: the c-means classified and defuzzified scan with $c=3$. Right: the c-means classified and defuzzified scan with $c=7$.

3. Experimental Protocols and Results

The method presented in the previous section was applied to solve the problem of registration of MR images of the head. A total of 200 two-dimensional and 240 three-dimensional registration experiments were performed using patient data from the database of the Cleveland Clinic Foundation. The purpose of this section is to present the protocol used for these experiments and also to provide a synopsis of the main results obtained.

The MR data used came from 10 different patients with various diseases. The data had the following characteristics:

- The patients had repetitive MR examination at two different times.
- For each time, T1- and T2-weighted axial interleaved studies that corresponded to the same position of the patient's head were performed.
- All the studies had 19 scans.
- All the studies had xy-plane resolution of 0.9 mm and z-axis resolution of 5 mm.

Using the data described in the previous section, a total of 200 two-dimensional experiments for alignment of a T2 to a T1 axial scan were performed. These experiments will be referred to as "20 displacement" experiments and were conducted according to the following rules:

- For each patient the tenth scan of each of the T1 and T2 studies of the first examination time were used.
- The T1 scan was used as the *reference* scan. The T2 scan was considered the *reslice* scan. The latter was rotated and translated using a standard set of 20 two-dimensional geometric transformations and then registered to the reference scan, giving 20 registration experiments per patient. The geometric transformations parameters were randomly selected using a random number generator in the range of -45 to +45 degrees for the xy rotation and -30 to +30 voxels for x and y translations.
- All the experiments were performed at full resolution. The size of the scans in voxels was 256x256 and the voxel size was 0.9 mm.

For the “20 displacement” experiments the Average Absolute Rotational Error per patient varied between 0.16 and 0.38 degs and the Average Absolute Translational Error per patient varied between 0.32 and 1.01 mms. Figure 3 gives a “20 displacement” registration example.

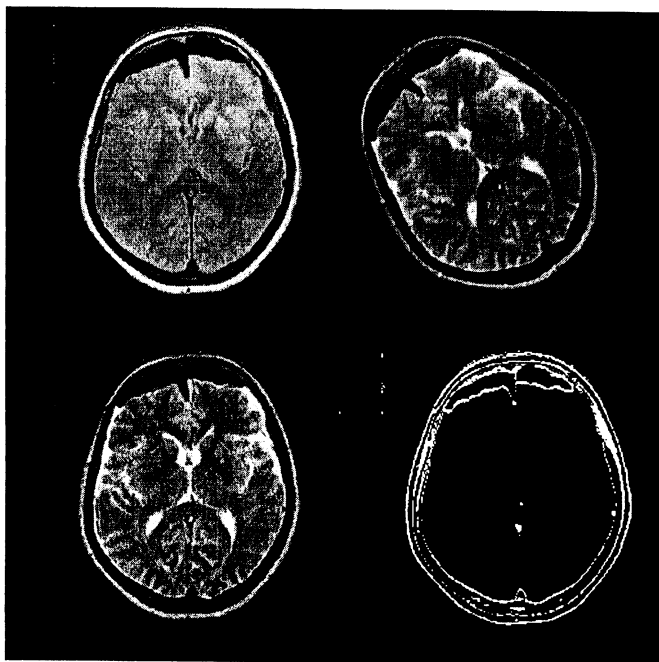


Figure 3: “20 displacement” T1-T2 registration example. Reference and reslice scans before and after registration. Top left: Reference T1 MR scan. Top right: Reslice T2 MR scan before registration. The two scans are rotated by 37.63 deg and translated by 23 voxels along the x-axis and 7 voxels along the y-axis. Bottom left: Reslice scan after registration. The registration error is 0.05 deg for xy rotation, 0 voxels for the x translation, and 2 voxels for the y translation. Bottom right: the white areas show the areas of non-overlap of the two scans after registration.

The three-dimensional registration accuracy of our method was tested with a total of 240 three-dimensional registration experiments. Two types of three-dimensional experiments were performed: The “10 displacement” experiments and the “different times” experiments. The “10 displacement” experiments were performed according to the following rules:

- For each patient the T1 and T2 studies of the first examination date were used.
- The T1 study was used as the reference study. The same study was also

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transformations and then registered to the reference study, giving 10 T1-T1 three-dimensional registration experiments per patient. The T2 study was also rotated and translated using the same three-dimensional geometric transformation set and then registered to the reference study, giving 10 T1-T2 three-dimensional registration experiments per patient. The rotational parameters of the geometric transformation set were randomly chosen within the limits of the adjustment values that were obtained from registration of patient data from different times. The translational parameters were kept within lower limits than those resulting from “different times” experiments, because they simulate centroid registration errors. The limits used were -30 degrees to +30 degrees for xy rotation, -10 degrees to +10 degrees for yz and zx rotations, -10 to +10 mm for x and y translations and -5 to +5 mm for z translation. The resulting set of the 10 three-dimensional geometric transformations is shown in table 1.

c) All the experiments were performed at half resolution using a voxel size of 1.8 mm.

d) The *Absolute Error (AE)* per transformation parameter was defined as the absolute difference of the adjustment value from the applied transformation parameter value. The average of the AEs for xy, yz, zx rotations was defined as the *Absolute Rotational Error (ARE)* per transformation and was computed in degrees. The *Absolute Translational Error (ATE)* per transformation was computed in millimeters by averaging the x, y and z translation AEs in voxels and then by multiplying the average value with the voxel size (1.8 mm). The *Average Absolute Rotational Error (AARE)* per patient was defined as the average of the AREs from all the transformations. Similarly, the *Average Absolute Translation Error (AATE)* per patient was defined as the average of the ATEs from all transformations.

Table 1: Geometric transformation set used for the “10 displacement” registration experiments

Transformation #	xy rotation (deg)	yz rotation (deg)	zx rotation (deg)	x translation (mm)	y translation (mm)	translation (mm)
1	-10.26	-6.94	-9.3	-9.2	-3.6	-3
2	12.42	2.32	-3.7	-4.6	-9.6	-2
3	-8.58	-4.38	1.9	8.4	6.9	
4	19.26	-7.2	-1.9	-1.66	-8	1
5	-26.58	-6.3	-2.16	-3.2	-7.6	
6	7.56	2.1	-7.6	0	-6.08	0
7	-5.82	-2.2	2.8	-8.4	-5.72	
8	-5.04	4.2	-4.04	4.2	3	
9	-15.66	-5.14	6.04	8	-6.04	1
10	-9.24	6.44	-6.7	-0.5	1.48	2

The “*different times*” experiments were performed in the following way:

- a) For each patient the T1 study of the first examination date and the T1 and T2 studies of the second examination date were used.
- b) The T1 study of the first examination date was considered as the *reference* study. The T1 and T2 studies of the second examination date were considered as the *reslice* studies and were both registered to the T1 study of the first examination date.
- c) The experiments were performed first at half and then at full resolution, giving four “*different times*” registration experiments per patient.

For the “10 displacement” T1-T1 registration the Average Absolute Rotational Error per patient varied between 0.17 and 0.42 degrees with an average value of 0.24 degs, whereas the Average Absolute Translational Error per patient varied between 0 and 0.03 voxels with an average value of 0.02 voxels. For the T1-T2 “10 displacement” experiments the average values are 0.36 for AARE (range, 0.23 to 0.49 degrees) and 0.2 voxels for AATE (range, 0.03 to 0.53 voxels). It can be seen that no significant loss in accuracy is measured when going from T1-T1 to T1-T2 registration. This result shows that our method is not affected by the differences in signal distributions and therefore it can be used for cross-modality registration. These results were verified with the “*different times*” experiments which additionally showed that the accuracy of the method is not affected by the deterioration in the imaging resolution for voxel sizes up to 1.8 mms.

Figure 4 shows an example of “10 displacement” three-dimensional registration in terms of the isosurface renderings of the two volumes before and after registration.

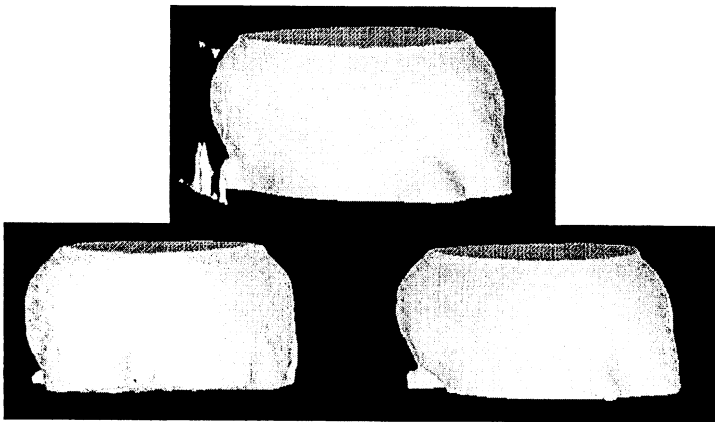


Figure 4: Worst-case example of T1-T2 “10 displacement” registration experiments. Top: Reference T1 volume. Bottom left: Reslice T2 volume before registration. Bottom right: Reslice T2 volume after registration.



Figure 5 gives an example of “different times” three-dimensional registration experiments in terms of the scans # 4, 10 and 16 of the two studies before and after registration.



Figure 5: Illustration of the “different times” three-dimensional registration experiments. First row: Scans # 4, 10, 16 of reference image study. Second row: Scans # 4, 10, 16 of reslice image study before registration. Third row: Scans # 4, 10, 16 of reslice image study after registration. Fourth row: White areas show the areas of mismatch between the studies of rows 1 and 3.

4. Discussion

Two different approaches to the solution of the problem of medical image registration exist: the iterative approach represented by the correlation and surface matching methods and the analytic approach represented by the principal axes method. The subject of this paper was the presentation of a new iterative method for three-dimensional image registration. The method developed uses a registration criterion, similar to the ratio image uniformity correlational criterion presented by Woods et al.[2,3]. As it was shown, the modifications made to the criterion together with the new way that it is minimized, allowed the use of the surface as the main registration feature and therefore the method can no longer be characterized as correlational.

The accuracy of the method for T1-T1 and T1-T2 MR image three-dimensional registration was evaluated using the "10 displacement" technique that gave rotational and translational errors less than 1 degree and 1 voxel. Several results showed also that the behavior of the method is not affected by the differences in signal intensities in the two volumes. When going from T1-T1 to T1-T2 "different times" experiments, the final adjustment values and the adjustments with each iteration do not change significantly. The same holds for the errors as computed with the "10 displacement" technique: these do not deteriorate when studies of different signal intensities are registered. This result shows also either the suitability of the fuzzy c-means for surface definition with MR data or the insensitivity of the method to noise and minor surface differences. Additional studies regarding the effect of noise on the performance of the method are needed. The deterioration in the imaging resolution was not found to affect significantly the performance of the method as measured by the rotational errors. The ability of the method to perform well at lower resolutions is an important feature because it increases the speed of the registration procedure.

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