Implementation of nonlinear registration of brain atlas based on piecewise grid system

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ABSTRACT

In this paper, a multi-step registration method of brain atlas and clinical Magnetic Resonance Imaging (MRI) data based on Thin-Plate Splines (TPS) and Piecewise Grid System (PGS) is presented. The method can help doctors to determine the corresponding anatomical structure between patient image and the brain atlas by piecewise nonlinear registration. Since doctors mostly pay attention to particular Region of Interest (ROI), and a global nonlinear registration is quite time-consuming which is not suitable for real-time clinical application, we propose a novel method to conduct linear registration in global area before nonlinear registration is performed in selected ROI. The homogenous feature points are defined to calculate the transform matrix between patient data and the brain atlas to conclude the mapping function. Finally, we integrate the proposed approach into an application of neurosurgical planning and guidance system which lends great efficiency in both neuro-anatomical education and guiding of neurosurgical operations. The experimental results reveal that the proposed approach can keep an average registration error of 0.25mm in near real-time manner.

Keywords: Brain Atlas, Nonlinear Registration, Thin-Plate Splines, Piecewise Grid System

1. INTRODUCTION

In recent years, brain surgery related research which focused on exploring the brain mystery, treating diseases and developing the technology of artificial intelligence has become more and more important in worldwide area. As the most complicated organ and central neuro-system, it controls fiber and nucleus group spread all over the brain. The structure of the brain, especially the internal part, provides basic evidence for solid directional anatomy and neurosurgery. Brain atlas is a simple, distinct and convenient tool in neuro-anatomical education. It helps the surgeons by choosing reasonable intervention method and surgery planning path through 3D visual model, guiding image segmentation applied in image analysis and inspecting pathology as well as exploring how brain works in modeling and imitation. [1]

Medical imaging is one of the maturely developed techniques and serves as one of the major tools for clinical diagnosis efficiently. Some functional images, such as Positron Emission Tomography (PET) and the Single Photon Emission Computed Tomography (SPECT) images, show the brain activities of uptake by different parts of the brain responding to different stimuli, which are the patient's response to illumination and changes in mental concentration. However, the anatomical structure in these functional images is limited because of poor spatial resolution, in most cases, even insufficient counting statistics [2]. Hence, in the analysis of functional images, the corresponding structural information is often indispensable. Generally, the biological structural information can be derived from Magnetic Resonance Imaging (MRI) or Computerized Tomography (CT) which presents the anatomic structure is important to research, diagnosis, and treatment of brain disease [3, 4]. Registration of medical images obtained from different imaging techniques is necessary to pinpoint the location of important brain landmarks [5, 6]. And the synthesis information of the functional and structural images is always strongly required for the clinical use of medical images [7, 8].

As the important structure of the brain, full of nerve fiber in a limited space, of great complexity, imperceptible and illegible in its boundary, it is very difficult to identify the wispy structure of brain in current imaging technology by our naked eye even under the clearest MRI data. So we have to make good use of some standard brain atlas which contains

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adequate information of topology and hierarchy. Although three-dimensional brain atlas provides the global view for doctors, there is still difference from the patient's data since each brain structure is unique. For the huge difference of

MIPPR 2007: Medical Imaging, Parallel Processing of Images, and Optimization Techniques, edited by Jianguo Liu, Kunio Doi, Patrick S. P. Wang, Qiang Li, Proc. of SPIE Vol. 6789, 678905, (2007) · 1605-7422/07/$18 · doi: 10.1117/12.749956

different individuals, we have to use registration method to map the topology and hierarchy information of brain atlas into the patients' image data, and tag the organization of ROI, which has great significance and improvement in diagnosing and the neuro-anatomical education.

Several methods for the registration of brain atlas have discussed in the literature [9, 10]. The most common approach is to employ an affine transform do the basic transfer, zoom or rotation or use the Thin-Plate Splines (TPS) model. However, global nonlinear registration is very time-consuming, although it is much more precise than linear registration. And doctors mostly pay merely attention to particular ROI. So a hybrid registration method we call piecewise nonlinear registration is proposed. In this paper, we proposed a multi-step method to implement the nonlinear registration of brain atlas and patient data based on piecewise grid system (PGS).

This paper is organized as follows. The deformation theory of registration of patient data and brain atlas is presented in Section Ⅱ. The descriptions of the data we use for experiment are given in Section Ⅲ, some simulation experiments and the application results are shown in Section Ⅳ. Section Ⅴ summarizes the conclusions of this paper.

2. METHODOLOGY

Considering of the low resolution and the asymmetry of the brain atlas, a multi-step registration method is employed. At first, the patient data and the brain atlas are transformed into the uniform coordinate system. Then, we match the brain atlas and the patient data using the linear method by PGS and Piecewise Linear Registration (PWL). After global registration, TPS transform is conducted to implement the local registration so as to make sure that the internal structures match with the counterparts. The whole procedure is organized in next steps.

2.1. Coordinate system transformation method

In order to match the MRI and the brain atlas, a global rigid transformation including rotation between the two coordinate systems is employed. We transfer the brain atlas into the coordinate of the patient data and define the coordinate below: the line connected the anterior commissure (AC) and posterior commissure (PC) is axis Y, Y-Z plane defined as lengthways cranny (between the hemisphere and the central of the sagittal) and Axis x is defined as the vertical line of axis y and z.

The key point of this part is how to identify the AC and PC points. An interactive method is conducted in our application, for the AC and PC points are two characterized points which are easily recognized for neurosurgeon.

2.2. Linear registration method

Although two coordinate systems have been unified, it is still very difficult to obtain the patient's anatomical structure of the brain from the brain atlas. We have to conduct a scale transformation in three dimensions, extend or shrink, so as to map the brain atlas into the MRI in a global view.

The PGS is the base of the transformation between the patient data and the brain atlas. PGS divided the brain area into 12 sub regions based on eight feature points (AC, PC, the most left point of the temporal cortex, the most right point of the temporal cortex, the most anterior points of the frontal cortex, the highest point of the occipital cortex and the lowest point of the temporal cortex). The process is in two steps: locate the boundary of the brain to create the PGS and conduct local PWL registration based on PGS.

2.2.1. Create the PGS

We locate the anterior, posterior, left, right, highest and lowest boundary on patient data. Then the brain area can be divided into 12 sub regions by central sagittal of hemisphere, double commissure plane and two coronal planes which get across the AC and PC points. The sketch map of PGS is shown as figure 1.

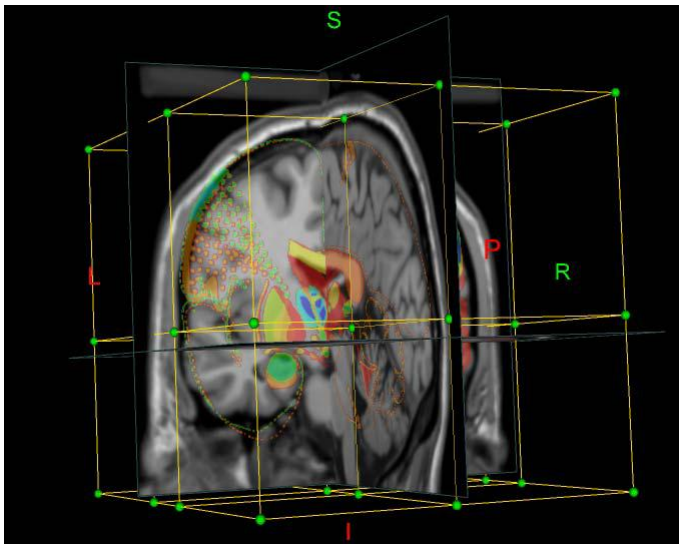


Fig.1. the sketch map of 12 sub regions

2.2.2. Local PWL registration based on PGS

Following the former method we can map the brain atlas to the patient data in a global view. As every control point in the PGS can be moved, an interactive way is conducted which can improve the precision of the registration of ROI. According to the proportional relation of the original and the target gird, all the points in the original grid are transferred into the target grid. We can get the transform as following formulation (1):

$$T = T_0 + (P - S_0) * T_{ext} / S_{ext} \quad (1)$$

Where T_0 and S_0 are the points in target and original grid and T_{ext}/S_{ext} is the proportional relation of the original and the target grid.

After coordinate unification and local PWL registration, we map each slice of the MRI data to the brain atlas according to the coordinate in the space. But this method has its restriction that it can't fully adapt to the complex brain structure. So following nonlinear registration method is indispensable.

2.3. Nonlinear registration method:

As there is not enough gray level information in the brain atlas, the best way for us to do a nonlinear registration is based on landmark points such as the extreme lines and extreme points. Here, we use the TPS [11] model to match the patient data and the brain atlas. The TPS mapping function can be used to determine a deformation function according to two sets of corresponding control points on the relative images. To apply this mapping function, the matching information of the image distribution in space can be integrated effectively. It is an elastic interpolation transform method which obtains the vector level through the landmark points. This method is to transfer the edge and the landmark points in the Brain Atlas into MR image, produce best precision mapping relation. Suppose we select N pair of points in the Brain Atlas and the MRI, we will get a transformation L which is (N+4)*(N+4). The detail description of the image mapping technique will be included as follows.

2.3.1. Thin-Plate Splines technique

In this paper, we define two sets of coordinate array information as P_i and h_i. $P_i = (X_i, Y_i, Z_i)$ and $h_i = (X_i, Y_i, Z_i)$,which are the control points belonging to the brain atlas and the patient data, respectively. The mapping transformation Φ, which maps each coordinate point from brain atlas to the patient data based on the equation (2), can be determined after the matching computation. The coefficients of the determined mapping transformation depend on the numbers of the selected matching points shown in the equation (2).

$$\Phi(P) = a_1 + a_x x + a_y y + a_z z + \sum_{i=1}^{n} \omega_i U(P - P_i) \quad (2)$$

Where P=(x, y, z) are the coordinates of the images space. To determine the coefficients in equation (2.3.1), the estimation operation of the matrix W is formed as (n+4) *2, is defined as:

$$W = (\omega_1 \ldots \omega_n a_1 a_x a_y a_z)^T = L^{-1} M \tag{3}$$

Where the $\omega_1, \omega_2, \ldots, \omega_n$;a_1, a_x, a_y and a_z are the primary coefficients used in the TPS. The matrixes W can also be represented by L and M as shown in the equation (3). The matrix M is formed as (n+4)*2:

$$M = (h_1 h_2 \ldots h_n 0000)^T \tag{4}$$

Where $h_i = (X_i, Y_i, Z_i)$, I = 1, … , n, is the coordinate of selected control points in patient data. The matrix L is formed as (n+4)*(n+4) by combining the matrix K, matrix Q, and another zero matrix with (4*4) shown as follows:

$$L = \begin{bmatrix} K & Q \\ Q^T & 0 \end{bmatrix} \tag{5}$$

In order to determine the matrix L, the operation parameter K and Q are defined as that. The matrix K is

$$K = \begin{bmatrix} 0 & U_{12} & \cdots & U_{1n} \\ U_{21} & 0 & \cdots & U_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ U_{n1} & U_{n2} & \cdots & 0 \end{bmatrix} \tag{6}$$

Where $U(r) = r^2 \log r$ and $r_{ij} = |P_i - P_j|$ is the distance between arbitrary two selected control points in brain atlas. And the Q matrix is defined as equation (7):

$$Q = \begin{bmatrix} 1 & X_1 & Y_1 & Z_1 \\ 1 & X_2 & Y_2 & Z_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & X_n & Y_n & Z_n \end{bmatrix} \tag{7}$$

Where (X_i, Y_i, Z_i), I = 1… n, is presented as the coordinate of control points in patient data. To determine TPS mapping function, the most important step is to estimate the coefficients ($\omega_1, \omega_2, \ldots, \omega_n; a_1, a_x, a_y$ and a_z) by the equation (3), which defines the mapping transformation of the corresponding points between brain atlas and the patient data. When a coordinate (x, y, z) of arbitrary point P and the distance between two arbitrary points shown as ($|P-P_i|$) in patient data are substituted into equation (2), we can obtain the homogenous points in brain atlas.

2.3.2. Thin-Plate Splines in our application

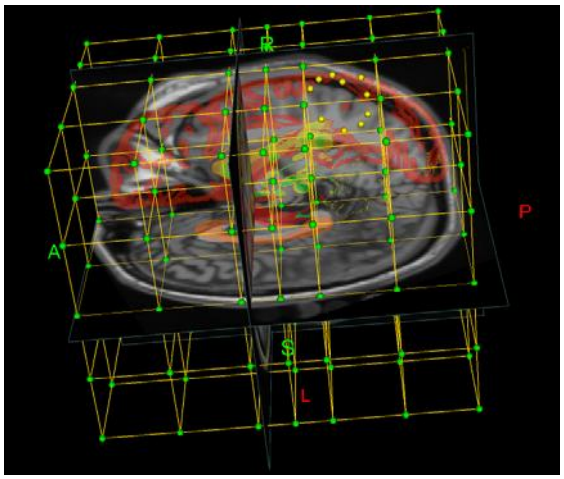


Fig.2 the sketch map of Thin-Plate Splines in our application

As most of the doctors pay much more attention to ROI, so we subdivide the PGS according to the requirement of the

doctor in much smaller part, in our application. Then we choose the landmark within the sub regions and drag these points to corresponding place in patient data. Finally, we apply the TPS method. The sketch map of this operation is shown as figure 2.

3. DATA

In registration, two images are used in our experiment, fixed image and moving image data. The fixed image is a clinical patient data and the moving image data is brain atlas. The clinical patient data we use for our experiment is in the dimension of 121*217*181, and the resolution in direction x, y and z are all 1mm. The brain atlas data we use is a standard brain atlas which is proposed by Talairach J and Tournoux P in a book [12] published in 1998. This Talairach-Tournoux brain atlas is a standard brain atlas widely used in tridimensional neurosurgery and computer aided radiology and widely accept by most of the neurologist for it includes a large amount of anatomizing and tridimensional functional information. It displays various structure of brain in three minc data from sagittal, axial and coronal in different resolution in x, y and z. As in the sagittal data the spacing is 0.84mm, 5mm, and 5mm.

4. RESULTS

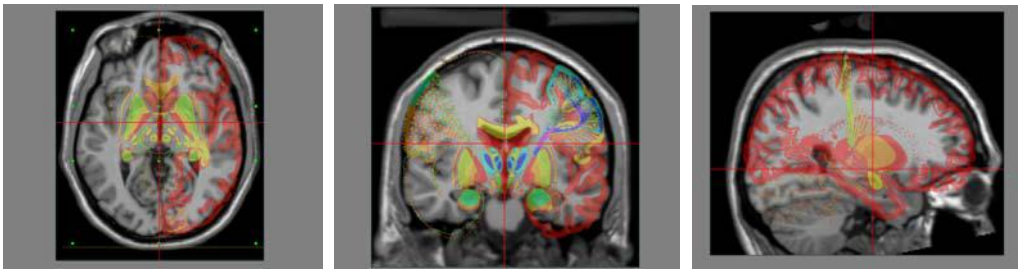
The experiment is employed on Windows-XP Professional operation system and developed under eclipse 3.1. The hardware environment is Intel P4 2.66G, 1G memory. Our application is based on the platform of atamai which help us in visualization.

At first, we employ linear registration of which the average error is limited within 0.5mm. In nonlinear registration part, we choose 10, 20, 30 points as the landmark points respectively, then we select 100 random points and calculate the difference after registration. The results are in table 1:

Table1: the error of different number of points (mm)

	1 0		2 0		3 0	
	average	max	average	max	average	max
x axis	0.24125	0.60170	0.21023	0.63431	0.19546	0.60683
y axis	0.28456	0.75235	0.19658	0.56988	0.17542	0.54323
z axis	0.20154	0.50674	0.18456	0.49796	0.15315	0.52429

We conduct the experiment for 100 times and the average time of nonlinear registration is 28 seconds. The result of the registration of brain atlas and the MRI data are show in Fig 3 (a), (b), (c) in sagittal, axial and coronal direction, respectively.



(a)The result of the sagittal (b) the result of the axial (c) the result of coronal

Fig.3. the result of the registration of brain atlas and the MRI

The user interface of our application system is shown as figure 4. In this application, we can load different MRI and brain atlas in high resolution or low resolution. We can also enlarge or reduce the image size as we like. This application is very convenient and easy to use.

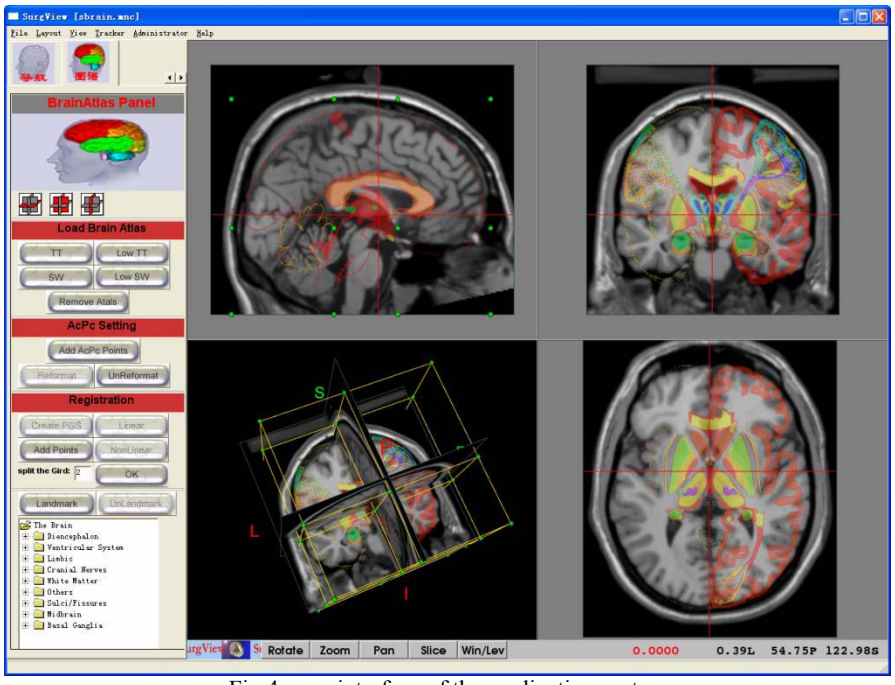


Fig.4. user interface of the application system

5. CONCLUSIONS

In this paper, we propose a multi-step nonlinear registration method of brain atlas and clinical patient data based on TPS and PGS, which is simple and results in high quality of both precision and stability. The experiments results reveal that the proposed approach keeps an average registration error of 0.25mm in near real-time manner.

Our future work is to design an automatic method in registration of brain atlas and to integrate the brain atlas registration part into the neurosurgery system, providing high-quality guide in surgery.

ACKNOWLEDGMENTS

The authors would like to thank the doctors from Shanghai Renji hospital in providing the experiment data and clinical advices. We are also grateful for the intellectual and financial support of National Natural Science Foundation (60571061), 863 research foundation (2007AA01Z312), and the Shanghai municipal research foundation (06dz15010).

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