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Image Registration Based on Boundary Mapping

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Abstract—**A new two-stage approach for nonlinear brain image registration is proposed. In the first stage, an active contour algorithm is used to establish a homothetic one-to-one map between a set of region boundaries in two images to be registered. This mapping is used in the second step: a two-dimensional transformation which is based on an elastic body deformation. This method is tested by registering magnetic resonance images to atlas images.**

I. Introduction

Registration of both intrasubject and intersubject brain images has been the subject of extensive study in the medical imaging literature. The various techniques that have been proposed can be classified into three major categories: polynomial transformations, similarity-based methods, and boundary-based methods. Polynomial transformations [1]–[3] apply a polynomial warping and determine the coefficients of the polynomial using linear regression if a sufficient number of landmark points is provided. Numerical instabilities and the requirement for a large number of landmark points typically limit these methods to the use of low degree polynomials [1]. Piecewise polynomial transformations have also been proposed. In particular, Bookstein describes a spline interpolation approach [4] which alleviates the problem of nonrealistic oscillations caused by polynomial interpolation. However, it also depends on the availability of a large number of landmark points.

Similarity-based methods have also been proposed. In [5] an elastic deformation, based on the cross-correlation coefficient between the images, is iteratively applied to one of the images until it matches the other. In [6], a visco-elastic deformation is proposed in a probabilistic formulation. Similarity-based methods assume that a rough initial registration is available and that the two images are very similar to each other. Since this assumption is not always satisfied in practice, false matches corresponding to local minima of the underlying energy functions can be obtained through these methods.

The third category of registration methods includes boundary-based methods, which use information from object boundaries in order to derive a full 2-D registration. Moshfeghi has proposed a method based on an iterative deformation of boundaries [7]. This method is computationally expensive and is sensitive to errors in the initial registration of the objects. In [8] and [9] the optimal rigid body deformation is found through an iterative search. Both of these approaches, based on the assumption of rigid body motion, are valid for intrasubject imaging and are not generally applicable to intersubject registration problems.

The two-frame motion estimation problem is very similar to the image registration problem and has an extensive body of related literature. Both region-based techniques [10] and boundary-based techniques [11] have been proposed. Generally, these techniques are either restricted to small deformations or require similar image modalities, which limits their application to those registration problems that satisfy these requirements.

In this paper we propose a boundary approach which decomposes the registration problem into two steps. In the first step we identify homologous brain regions in two images to be registered (e.g., cortex, ventricles, etc.), and we establish a one-to-one mapping between their boundaries. In the second step, we deform the collection of mapped boundaries in one image into those in the other image. The rest of the image is brought into registration by solving the equations describing the deformation of an elastic body using the boundary deformations as input.

II. Elastic Image Warping Using Homothetic Boundary Mapping

A. Homothetic Mapping

Let $I_1(\boldsymbol{x}) = I_1(x,y)$ and $I_2(\boldsymbol{u}) = I_2(u,v)$ be the image intensity functions of a pair of images to be registered, defined in the image domains $\mathcal{D}_1$ and $\mathcal{D}_2$, respectively. Image registration is the problem of finding a nonlinear transformation $\boldsymbol{U}(\boldsymbol{x}) = (U(x,y), V(x,y))$ that maps $\mathcal{D}_1$ into $\mathcal{D}_2$, so that the resulting image $I_3(\boldsymbol{U}(\boldsymbol{x}))$ is in anatomical correspondence with $I_2(\boldsymbol{u})$. The approach proposed in this paper obtains a transformation $\boldsymbol{U}$ through the two-step procedure described next.

In the first step of our approach we identify J corresponding regions in the two images (e.g., the parenchyma, the ventricles, etc.). Subsequently, we create a one-to-one mapping between the boundaries of these regions, as shown in Fig. 1. This is a key step in our approach because it automatically establishes a large number of corresponding points in the two images. A fundamental assumption made in this first step is that the boundary of a region in one image can be transformed into an analogous boundary in the second image *homothetically*, i.e., by a uniform scaling of its length and an arbitrary length-preserving bending. We demonstrate in the experiments of Section III that this assumption yields good point correspondences between homologous boundaries. Also, in Section IV we discuss a potential extension to allow nonuniform boundary scaling.

In order to obtain the homothetic mapping between two boundaries, an active contour algorithm which is described in detail in [12] is used to extract the boundary of each of the J selected regions in each image. The obtained curves are reparametrized by a constant speed parameterization and therefore have points evenly spaced along the J boundaries. Finally, a circular shift is applied to all curves of one of the two images to be registered, resulting in an optimal match of the curvature along homologous boundaries. Resulting from this procedure are the points $\boldsymbol{x}_{0k}, \boldsymbol{x}_{1k}, \cdots, \boldsymbol{x}_{M_k k}, k = 1, \cdots, J$, which define the J boundaries in the first image, and the points $\boldsymbol{u}_{0k}, \boldsymbol{u}_{1k}, \cdots, \boldsymbol{u}_{M_k k}, k = 1, \cdots, J$, which define the J

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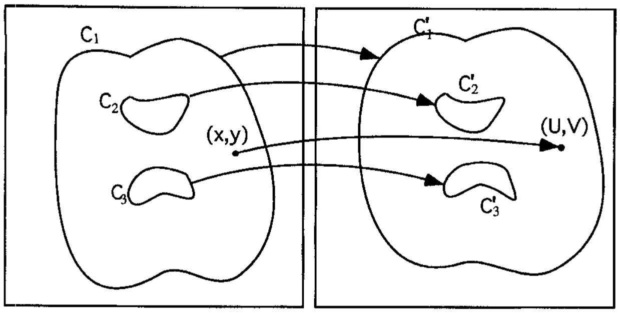
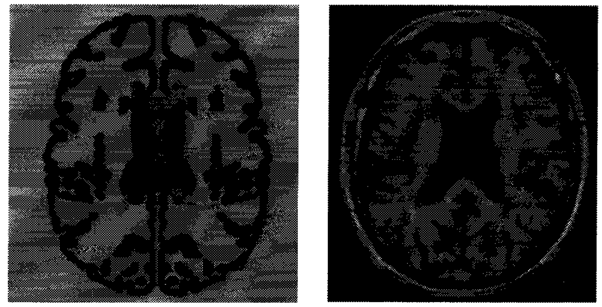


Fig. 1. A mapping between a set of boundaries in the two images guides a two-dimensional elastic transformation.



(a) (b)

Fig. 2. (a) A digitized Talairach atlas image. (b) The corresponding MR image.

boundaries in the second image. Since these points are equidistantly distributed along the J pairs of boundaries, they define a homothetic mapping between corresponding boundaries. In particular, for each $i = 0, \cdots, M_k$ and $k = 1, \cdots, J$, the point $\boldsymbol{x}_{ik}$ and the point $\boldsymbol{u}_{ik}$ are corresponding points. This collection of corresponding points, largely defined automatically, is used in the transformation of the following section.

B. Elastic Deformation Transformation (EDT)

The transformation proposed in this section is an *elastic deformation transformation* (EDT), which models images as elastic sheets which are warped by an external force field applied to those points in $\mathcal{D}_1$ that are part of the J boundaries mapped in the first step, encouraging them to deform to the coordinates of their corresponding points in $\mathcal{D}_2$. Because of its smoothness, elastic warping tends to preserve the shape and relative position of brain structures. Therefore it is appropriate for our problem since the structure of the brain is fairly consistent across individuals. Moreover, it is well-suited to the nature of our landmarks, which are curves bounding anatomical regions, in contrast to interpolation methods which are more suitable when the landmarks are a collection of scattered points marking distinct anatomical features [4].

Let $q(x, y)$ be an indicator function defined for each point $(x, y) \in \mathcal{D}_1$ such that $q(x, y)$ is unity when (x, y) has a point of correspondence, say $(f^u(x, y), f^v(x, y))$, in $\mathcal{D}_2$ and is zero otherwise. Points of correspondence are given by $\boldsymbol{x}_{0k}, \cdots, \boldsymbol{x}_{M_k k}$ and $\boldsymbol{u}_{0k}, \cdots, \boldsymbol{u}_{M_k k}, k = 1, \cdots, J$. We define the functions $(U(\cdot, \cdot), V(\cdot, \cdot))$ to be a solution to the equations describing the deformation of an elastic sheet [13]

$$\mu\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) + (\lambda + \mu)\frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right) + q(x, y)(f^u(x, y) - U(x, y)) = 0, \tag{1a}$$

$$\mu\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) + (\lambda + \mu)\frac{\partial}{\partial y}\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right) + q(x, y)(f^u(x, y) - V(x, y)) = 0. \tag{1b}$$

The boundary conditions required to solve (1) are chosen so that the bounding box of the brain in $\mathcal{D}_1$ maps to the bounding box of the brain in $\mathcal{D}_2$, and they are determined automatically using the leftmost, the rightmost, the uppermost, and the lowermost points of the active contours obtained at the first step. In order to solve the problem defined by (1), we discretize (1) and solve the resulting linear system iteratively.

The constants λ and μ determine the degree to which EDT conforms to the boundary mapping established in the first step. If λ and μ are chosen small, EDT tends to preserve the homothetic boundary mapping. If they are chosen large, smoother deformations are obtained. We have found that the precise values of λ and μ have a relatively small effect on the transformation obtained through EDT. In the experiments herein we have chosen λ and μ empirically.

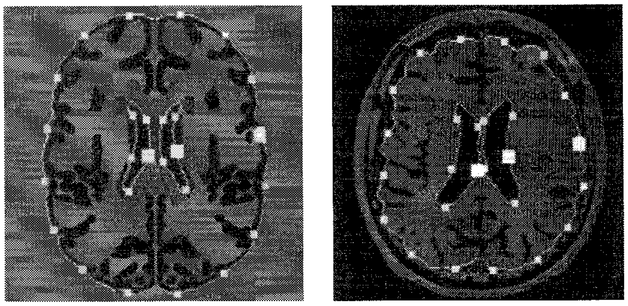
There are certain similarities between our technique and the registration technique in [5]. There are also similarities with the optical flow formulation of [10] and the motion estimation of [14]. In particular, all methods are based on some type of smooth deformation between images. However, there is a fundamental difference. Since the methods in [5], [10], and [14] define the external forces based on a local optimization, they require that the images are very similar to each other and differ only by a small deformation. EDT, on the other hand, determines the external forces through the correspondences established by the homothetic mapping. Since corresponding boundary points are not necessarily close to each other, the images to be matched can differ considerably without this affecting the performance of EDT. This property of EDT is important in many applications of clinical interest, such as the study of anatomical abnormalities of Alzheimer's disease patients, where large deformations of the shape of the brain are present, and therefore it is not always possible to obtain a good initial registration for all brain regions simultaneously (see Section III).

III. Experimental Results

In the experiments of this section we used the Talairach atlas transaxial image shown in Fig. 2(a) (Fig. 114 in [15]) and the transaxial MR image shown in Fig. 2b (SPGR acquisition, 35ms/5ms TR/TE). The procedure described in Section II-A was applied to both images in Fig. 2 using one active contour for the outer cortical boundary (500 points), one for the left lateral ventricle (150 points), and one for the right lateral ventricle (150 points). The resulting contours are shown in Fig. 3 (thin curves).

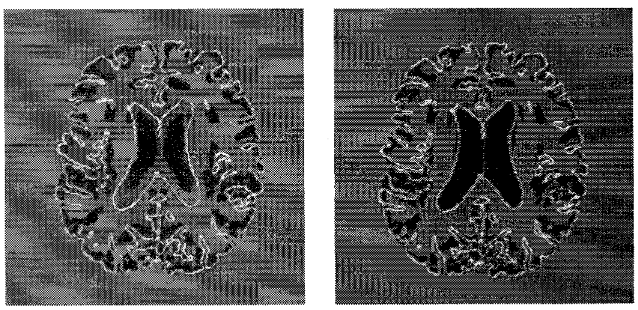
In order to evaluate how well the homothetic mapping created points of correspondence in this example, we selected every 30th point of each of the three active contours in each image. The selected points are shown in Fig. 3 as thick dots; the thickest dot in Fig. 3 is the first point of each active contour. Fig. 3 shows a very good point-to-point correspondence, considering the fact that the procedure was nearly automated.

EDT was applied next ($\lambda = \mu = 1.5 \times 10^{-9}$), transforming the atlas image to the MR image. First, we used only the outer cortical contours as points of correspondence; the resulting image is shown in Fig. 4(a) superimposed on the cortical and ventricular outlines of the MR image. As Fig. 4(a) shows, a good match was obtained at the cortical area, but a poor match was obtained around the ventricular area. This is due to the ventricular enlargement, typical in elderly individuals. We then used both the cortical and the ventricular



(a) (b)

Fig. 3. The final configurations of the active contours used for the cortical and ventricular boundaries. A selection of these points, shown as thick dots, demonstrates a good point-to-point correspondence obtained through the homothetic boundary mapping.



(a) (b)

Fig. 4. (a) The warped atlas image using only the outer cortical points. (b) The warped atlas image using the outer cortical and the ventricular boundary points. Both images are superimposed on the cortical and the ventricular boundaries of Fig. 2(b).

contours as points of correspondence; the resulting image is shown in Fig. 4(b), superimposed on the same outlines as the ones in Fig. 4(a). A good match was now obtained throughout the whole image.

In order to obtain a quantitative measure of the registration accuracy in this example, we manually selected 18 points in the atlas image and their anatomically corresponding points in the MR image, as shown in Fig. 5(a) and (b), respectively. Fig. 5(c) shows the transformed landmark points of Fig. 5(a) and the points of Fig. 5(b) superimposed on the transformed atlas image, for the transformation of Fig. 4(a). The mean and the standard deviation of the distances between the points in Fig 5(c) were 4.57 mm and 3.3 mm, respectively. Fig. 5(d) shows the transformed landmark points of Fig. 5(a) and the points of Fig. 5(b) superimposed on the transformed atlas image, for the transformation of Fig. 4(b). The mean and the standard deviation of the distances between the points in Fig. 5(d) were 3 mm and 2.8 mm, respectively, a considerable improvement over the error in Fig. 5(c).

IV. Discussion

We have presented a new approach for brain image registration based on a two-step procedure. In the first step we obtain a one-to-one homothetic mapping between two sets of boundary curves using an active contour algorithm, establishing the correspondence of a large number of points with minimal human intervention. The second step transforms the coordinate space of one image into that of the other using these matched boundaries. EDT, a nonlinear elastic transformation, was proposed to bring the remaining image points into registration.

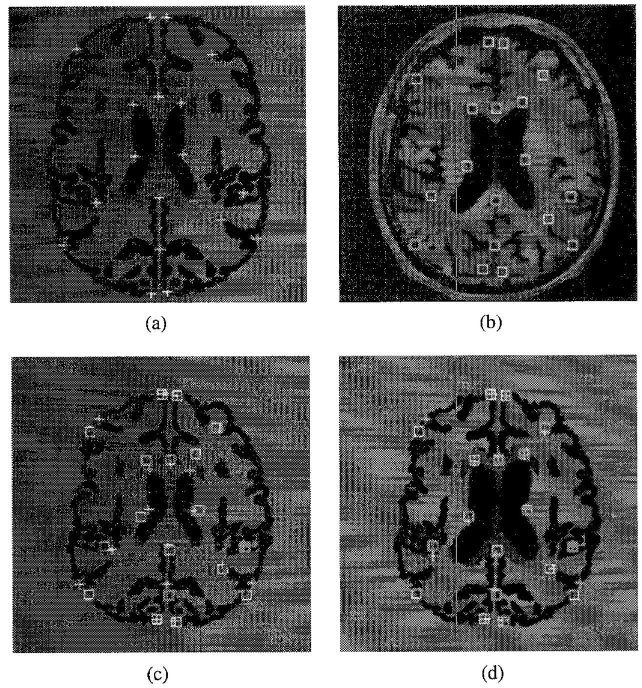


Fig. 5. Registration error measurement: (a) the points selected from the atlas image, (b) their corresponding points in the MR image, (c) the transformed points of (a) superimposed on the points in (b), using only the outer cortical active contour points in the elastic warping, and (d) the transformed points of (a) superimposed on the points in (b), using both the outer cortical and the ventricular active contour points in the elastic warping.

Many modifications and improvements to this basic approach are possible. In particular, since we demonstrated that good point-to-point correspondence is achieved in the first step of our approach, it could in principle be used in conjunction with any landmark-based approach. For example, the approach of Bookstein [4] could be used in the second step instead of EDT, with the points found in the first step. Finally, our registration could be followed by a region-based elastic transformation, such as in [5] and [6].

In our development throughout the paper we have assumed that EDT is applied on a slice-by-slice basis, after the alignment of the z-axis of the two datasets and a scaling along the z-axis which brings MR and atlas slices into a rough correspondence. Although there are several applications of this 2-D registration method [16] and [17], extension of this approach to 3-D is also possible through the use of deformable surfaces [18] instead of active contours. Since, unlike the 2-D case, a homothetic map between two surfaces does not always exist, in 3-D a nearly-homothetic map would be sought, which would define a point-to-point mapping between homologous regions within the brain. EDT can then be defined in a completely analogous way.

A key assumption used in the approach herein is that the homothetic mapping between corresponding boundaries yields good points of correspondence. It was shown to perform well in the example study; however, nonhomothetic mappings could provide better anatomical correspondence in some cases. In these cases, suppose one or more points on the region boundaries were known to be in correspondence. Then these points can be used as knots in the active contour, where the map would be homothetic between knots, but would be nonhomothetic overall. Furthermore, such points could in principle be derived automatically using nonlinear curvature matching techniques. The development of such techniques is a future direction of our research.

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