A Topology Preserving Method for 3-D Non-rigid Brain Image Registration

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Abstract. This paper deals with topology preservation in the framework of 3-D image registration using a multiscale parametric deformation field model. Using a B-spline deformation field yields a polynomial closed form expression for the jacobian. Ensuring positivity of the jacobian guarantees topology preservation. Due to the intricate form of the jacobian in the 3-D case, we have to resort to interval analysis techniques to solve the corresponding optimization problem.

1 Introduction

Inter-subject or atlas-subject non-rigid brain image registration has received considerable attention during the last decade [1]. The purpose is to estimate long-distance and highly nonlinear deformations corresponding to anatomical variability between individuals without violating topology as anatomical structures, for non-pathological cases, have the same topology across individuals. In order to enforce topology preservation, the transformation should be one-to-one, which is ensured by the positivity of the jacobian. We are thus facing a constrained optimization problem. This work is the 3-D extension of [2], which only tackles topology preserving mappings in the 2-D case.

2 Method

The transformation between both images is parameterized at different scales, using a decomposition of the deformation vector field $\mathbf{u}$ over a sequence of nested subspaces. The bases of these spaces are generated from dilated and translated versions of a single compactly supported scaling function ϕ, corresponding to a B-spline function. At resolution l, the parameterization of $\mathbf{u}$ is given by:

$$\mathbf{u}^l(x,y,z) = \begin{bmatrix} u_x^l(x,y,z) \\ u_y^l(x,y,z) \\ u_z^l(x,y,z) \end{bmatrix} = \begin{bmatrix} \sum_{i,j,k} a_{x;i,j,k}^l \phi_{i,j,k}^l(x,y,z) \\ \sum_{i,j,k} a_{y;i,j,k}^l \phi_{i,j,k}^l(x,y,z) \\ \sum_{i,j,k} a_{z;i,j,k}^l \phi_{i,j,k}^l(x,y,z) \end{bmatrix}$$

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where $\phi^l_{i,j,k}(x,y,z) = 2^{\frac{3l}{2}}\phi(2^l x - i)\phi(2^l y - j)\phi(2^l z - k)$. Let $\Omega^l_{i,j,k}$ the support of $\phi^l_{i,j,k}$. The parameters of this model are estimated by minimizing the quadratic cost function $E(\mathbf{u}) = \int_\Omega \mid I_1(\mathbf{s}) - I_2(\mathbf{s} + \mathbf{u}(\mathbf{s})) \mid^2 \mathbf{ds}$, where Ω is the bounded domain defined by the images and I_2 is the floating image to be mapped onto image I_1.

The jacobian J of the transformation must be positive on the whole domain Ω to preserve topology. The parameters $[a^l_{x;i,j,k}, a^l_{y;i,j,k}, a^l_{z;i,j,k}]$ of $\mathbf{u}$ are updated blockwise along a direction $\mathbf{d}$ in a Gauss-Seidel scheme. On the corresponding updated block $\Omega^l_{i,j,k}$, the jacobian has a closed form polynomial expression of the space variables and the displacement step δ. As its expression is linear in δ, the maximum (resp. minimum) of J on $\Omega^l_{i,j,k}$ is a convex (resp. concave) function of δ. An admissible set of steps $[0, \delta_{max}]$ is determined using interval analysis techniques [4] to minimize E while satisfying the positivity constraint.

3 Results

To highlight the contribution of topology preservation, we present on Fig. 1 the matching between two 3-D 128^3 MR brain images of different patients, focusing our attention on segmented ventricles. These registrations were performed up to scale $l = 5$ (corresponding to 89373 parameters) with a computational burden lower than 30 minutes on a PC workstation (2.4 GHz).

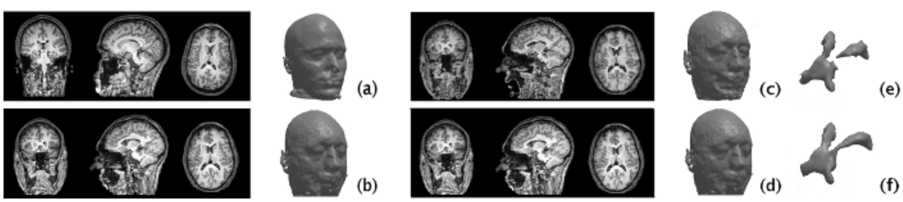

Fig. 1. Non-rigid matching between two different patients: (a) source image; (b) target image; (c) result of matching without any constraint; (d) result of matching with the positivity constraint $J > 0$; (e) segmented registered ventricle without any constraint (notice the tearing); (f) segmented registered ventricle with the positivity constraint.

References

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