

# Genus Zero Surface Conformal Mapping and Its Application to Brain Surface Mapping

Xianfeng Gu, Yalin Wang, Tony F. Chan, Paul M. Thompson, Shing-Tung Yau

**Abstract**—It is well known that any genus zero surface can be mapped conformally onto the sphere and any local portion thereof onto a disk. However, it is not trivial to find a general method which computes a conformal mapping between two general genus zero surfaces. We propose a new variational method which can find a unique mapping between any two genus zero manifolds by minimizing the harmonic energy of the map. We demonstrate the feasibility of our algorithm by applying it to the cortical surface matching problem. We use a mesh structure to represent the brain surface. Further constraints are added to ensure that the conformal map is unique. The conformal mapping is also used for spherical harmonic transformation for the purpose of brain surface compression and rotation-invariant shape analysis. Empirical tests on MRI data show that the mappings preserve angular relationships, are stable in MRIs acquired at different times, and are robust to differences in data triangulation, and resolution. Compared with other brain surface conformal mapping algorithms, our algorithm is more stable and has good extensibility.

**Index Terms**—Conformal Map, Brain Mapping, Landmark Matching, Spherical Harmonic Transformation.

## I. INTRODUCTION

RECENT developments in brain imaging have accelerated the collection and databasing of brain maps. Nonetheless, computational problems arise when integrating and comparing brain data. One way to analyze and compare brain data is to map them into a canonical space while retaining geometric information on the original structures as far as possible [1]–[5]. Fischl et al. [1] demonstrate that surface based brain mapping can offer advantages over volume based brain mapping, especially when localizing cortical deficits and functional activations. Thompson et al. [4], [5] introduce a mathematical framework based on covariant partial differential equations, and pull-backs of mappings under harmonic flows, to help analyze signals localized on brain surfaces.

### A. Previous work

Conformal surface parameterizations have been studied intensively. Most works on conformal parameterizations deal with surface patches homeomorphic to topological disks. For

X. Gu is with the department of Computer and Information Science and Engineering, University of Florida, FL 32611, gu@cise.ufl.edu.

Y. Wang is with the Mathematics Department, UCLA, CA 90095, yl-wang@math.ucla.edu.

T. F. Chan is with the Mathematics Department, UCLA, CA 90095, chan@math.ucla.edu.

P. M. Thompson is with the Laboratory of Neuro Imaging, Department of Neurology, UCLA School of Medicine, thompson@loni.ucla.edu.

S.-T. Yau is with the Department of Mathematics, Harvard University, yau@math.harvard.edu.

surfaces with arbitrary topologies, Gu and Yau [6] introduce a general method for global conformal parameterizations based on the structure of the cohomology group of holomorphic one-forms. They generalize the method for surfaces with boundaries in [7].

For genus zero surfaces, there are five basic approaches to achieve conformal parameterizations.

- 1) *Harmonic energy minimization.* Eck et al. [8] introduce the discrete harmonic map, which approximates the continuous harmonic map [9] by minimizing a *metric dispersion* criterion. Desbrun et al. [10], [11] compute the discrete Dirichlet energy and apply conformal parameterization to interactive geometry remeshing. Pinkall and Polthier compute the discrete harmonic map and Hodge star operator for the purpose of creating a minimal surface [12]. Kanai et al. use a harmonic map for geometric metamorphosis in [13]. Gu and Yau in [6] introduce a non-linear optimization method to compute global conformal parameterizations for genus zero surfaces. The optimization is carried out in the tangent spaces of the sphere.
- 2) *Cauchy-Riemann equation approximation.* Levy et al. [14] compute a quasi-conformal parameterization of topological disks by approximating the Cauchy-Riemann equation using the least squares method. They show rigorously that the quasi-conformal parameterization exists uniquely, and is invariant to similarity transformations, independent of resolution, and orientation preserving.
- 3) *Laplacian operator linearization.* Haker et al. [3], [15] use a method to compute a global conformal mapping from a genus zero surface to a sphere by representing the Laplace-Beltrami operator as a linear system.
- 4) *Angle based method.* Sheffer et al. [16] introduce an angle based flattening method to flatten a mesh to a 2D plane so that it minimizes the relative distortion of the planar angles with respect to their counterparts in the three-dimensional space.
- 5) *Circle packing.* Circle packing is introduced in [2], [17]. Classical analytic functions can be approximated using circle packing. For general surfaces in  $\mathbb{R}^3$ , the circle packing method considers only the connectivity but not the geometry, so it is not suitable for our parameterization purpose.

Bakircioglu et al. use spherical harmonics to compute a flow on the sphere in [18] in order to match curves on the brain. Thompson and Toga use a similar approach in [19]. This flow field can be thought of as the variational minimizer of the

integral over the sphere of  $\int_L u$ , with  $L$  some power of the Laplacian, and  $u$  the deformation. This is very similar to the spherical harmonic map used in this paper.

### B. Basic Idea

Define a mapping  $f : M_1 \rightarrow M_2$  between two surfaces  $M_1$  and  $M_2$ , where the first fundamental forms of the two surfaces are  $ds_1^2 = \sum g_{ij} dx^i dx^j$  and  $ds_2^2 = \sum \tilde{g}_{ij} dx^i dx^j$ . We say  $f$  is a *conformal mapping* if  $f^* ds_2^2 = \lambda ds_1^2$ , where  $\lambda$  is a positive scalar and  $f^*$  is the pull back function.

$$f^* ds_2^2 = \sum_{mn} \left( \sum_{ij} \tilde{g}_{ij}(f(x)) \frac{\partial f^i}{\partial x^m} \frac{\partial f^j}{\partial x^n} \right) dx^m dx^n$$

Intuitively, all the angles on  $M_1$  are preserved on  $M_2$ . Figure 1 shows a conformal mapping example. Figure 1(a) shows a real male face. We conformally map it to a square as in 1(c) and get its conformal parameterization. We illustrate the conformal parameterization via the texture mapping of a checkerboard in Figure 1.

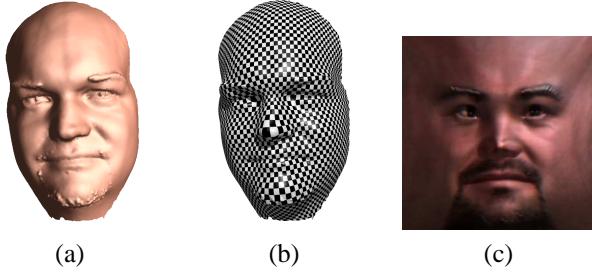


Fig. 1. Conformal surface parameterization examples. (a) is a real male face. (c) is a square into which the human face is conformally mapped. (b) is the conformal parameterization illustrated by the texture map. As shown, the right angles on the checkboard are well preserved on the surface in (b).

It is well known that any genus zero surface can be mapped conformally onto the sphere and any local portion thereof onto a disk. This mapping, a conformal equivalence, is one-to-one, onto, and angle-preserving. Moreover, the elements of the first fundamental form remain unchanged, except for a scaling factor (the so-called *Conformal Factor*). For this reason, conformal mappings are often described as being similarities in the small. Since the cortical surface of the brain is a genus zero surface, conformal mapping offers a convenient method to retain local geometric information, when mapping data between surfaces. Indeed, several groups have created flattened representations or visualizations of the cerebral cortex or cerebellum [2], [3] using conformal mapping techniques. However, these approaches are either not strictly angle preserving [2], or there may be areas with large geometric distortions [3]. In this paper, we propose a new genus zero surface conformal mapping algorithm [6] and demonstrate its use in computing conformal mappings between brain surfaces. Our algorithm depends only on the surface geometry and is invariant to changes in image resolution and the specifics of the data triangulation. Our experimental results show that our algorithm has advantageous properties for cortical surface matching.

Suppose  $K$  is a simplicial complex, and  $f : |K| \rightarrow R^3$ , which embeds  $|K|$  in  $R^3$ ; then  $(K, f)$  is called a mesh. Given two genus zero meshes  $M_1, M_2$ , there are many conformal mappings between them. Our algorithm for computing conformal mappings is based on the fact that for genus zero surfaces  $S_1, S_2$ ,  $f : S_1 \rightarrow S_2$  is conformal if and only if  $f$  is harmonic. All conformal mappings between  $S_1, S_2$  form a group, the so-called Möbius group. Figure 2 show some examples of Möbius transformations. We can conformally map the surface of the head of Michelangelo's David to a sphere. When we draw the longitude and latitude lines on the sphere, we can induce corresponding circles on the original surface (a) and (b). We apply a Möbius transformation to the sphere and make the two eyes become north and south poles. When we draw the longitude and latitude lines again (c), we get an interesting result shown in (d). Note all the right angles between the lines are well preserved in (b) and (d). This example demonstrates that all the conformal mapping results form a Möbius group.

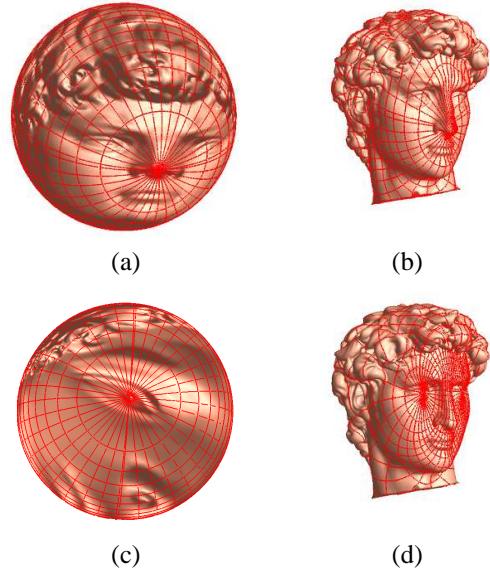


Fig. 2. Möbius transformation example. We conformally map the surface of the head of Michelangelo's David to a sphere. In (a), we select the nose tip as the north pole and draw longitude and latitude lines on the sphere. (b) shows the results on the original David head model. We apply a Möbius transformation on the sphere in (a) and make the two eyes become the north and south poles. When drawing the longitude and latitude lines on the sphere (c), we get an interesting configuration for the lines on the original surface (d).

Our method is as follows: we first find a homeomorphism  $h$  between  $M_1$  and  $M_2$ , then deform  $h$  such that  $h$  minimizes the harmonic energy. To ensure the convergence of the algorithm, constraints are added; this also ensures that there is a unique conformal map.

This paper is organized as follows. In Section II, we give the definitions of a piecewise linear function space, inner product and piecewise Laplacian. In Section III, we describe the steepest descent algorithm which is used to minimize the string energy. In Section IV, we detail our conformal spherical mapping algorithms. In Section V, the conformal parameterization is optimized by integrating landmark information. Section VI applies conformal mapping for spherical

harmonic transformation, and rotation-invariant shape analysis. Experimental results on conformal mapping for brain surfaces are reported in Section VII. In Section VIII, we compare our algorithm with other conformal mapping approaches used in neuroimaging. We conclude the paper in Section IX.

## II. PIECEWISE LINEAR FUNCTION SPACE, INNER PRODUCT AND LAPLACIAN

For the diffeomorphisms between genus zero surfaces, if the map minimizes the harmonic energy, then it is conformal. Based on this fact, the algorithm is designed as a steepest descent method.

This section formulates the mathematical concepts in a rigorous way. The major concepts, the harmonic energy of a map and its derivative, are defined. Because all the calculation is carried out on surfaces, we use the absolute derivative. Furthermore, for the purpose of implementation, we introduce the definitions in discrete form.

We use  $K$  to represent the simplicial complex,  $u, v$  to denote the vertices, and  $\{u, v\}$  to denote the edge spanned by  $u, v$ . We use  $f, g$  to represent the piecewise linear functions defined on  $K$ , use  $\vec{f}$  to represent vector value functions. We use  $\Delta_{PL}$  to represent the discrete Laplacian operator.

**Definition 1:** All piecewise linear functions defined on  $K$  form a linear space, denoted by  $C^{PL}(K)$ .

In practice, we use  $C^{PL}(K)$  to approximate all functions defined on  $K$ . So the final result is an approximation to the conformal mapping. The higher the resolution of the mesh is, the more accurate the approximated conformal mapping is.

**Definition 2:** Suppose a set of string constants  $k_{u,v}$  are assigned for each edge  $\{u, v\}$ , the inner product on  $C^{PL}$  is defined as the quadratic form

$$\langle f, g \rangle = \frac{1}{2} \sum_{\{u,v\} \in K} k_{u,v} (f(u) - f(v))(g(u) - g(v)) \quad (1)$$

The energy is defined as the norm on  $C^{PL}$ .

**Definition 3:** Suppose  $f \in C^{PL}$ , the string energy is defined as:

$$E(f) = \langle f, f \rangle = \sum_{\{u,v\} \in K} k_{u,v} \|f(u) - f(v)\|^2 \quad (2)$$

By changing the string constants  $k_{u,v}$  in the energy formula, we can define different string energies.

**Definition 4:** If string constants  $k_{u,v} \equiv 1$ , the string energy is known as the Tuette energy.

**Definition 5:** Suppose edge  $\{u, v\}$  has two adjacent faces  $T_\alpha, T_\beta$ , with  $T_\alpha = \{v_0, v_1, v_2\}$ , define the parameters

$$a_{v_1, v_2}^\alpha = \frac{1}{2} \frac{(v_1 - v_3) \cdot (v_2 - v_3)}{|(v_1 - v_3) \times (v_2 - v_3)|} \quad (3)$$

$$a_{v_2, v_3}^\alpha = \frac{1}{2} \frac{(v_2 - v_1) \cdot (v_3 - v_1)}{|(v_2 - v_1) \times (v_3 - v_1)|} \quad (4)$$

$$a_{v_3, v_1}^\alpha = \frac{1}{2} \frac{(v_3 - v_2) \cdot (v_1 - v_2)}{|(v_3 - v_2) \times (v_1 - v_2)|} \quad (5)$$

$$(6)$$

$T_\beta$  is defined similarly. If  $k_{u,v} = a_{u,v}^\alpha + a_{u,v}^\beta$ , the string energy obtained is called the harmonic energy.

The string energy is always a quadratic form. By carefully choosing the string coefficients, we make sure the quadratic form is positive definite. This will guarantee the convergence of the steepest descent method.

**Definition 6:** The piecewise Laplacian is the linear operator  $\Delta_{PL} : C^{PL} \rightarrow C^{PL}$  on the space of piecewise linear functions on  $K$ , defined by the formula

$$\Delta_{PL}(f) = \sum_{\{u,v\} \in K} k_{u,v} (f(v) - f(u)) \quad (7)$$

If  $f$  minimizes the string energy, then  $f$  satisfies the condition  $\Delta_{PL}(f) = 0$ . Suppose  $M_1, M_2$  are two meshes and the map  $\vec{f} : M_1 \rightarrow M_2$  is a map between them,  $\vec{f}$  can be treated as a map from  $M_1$  to  $R^3$  also.

**Definition 7:** For a map  $\vec{f} : M_1 \rightarrow R^3$ ,  $\vec{f} = (f_0, f_1, f_2)$ ,  $f_i \in C^{PL}, i = 0, 1, 2$ , we define the energy as the norm of  $\vec{f}$ :

$$E(\vec{f}) = \sum_{i=0}^2 E(f_i) \quad (8)$$

The Laplacian is defined in a similar way,

**Definition 8:** For a map  $\vec{f} : M_1 \rightarrow R^3$ , the piecewise Laplacian of  $\vec{f}$  is

$$\Delta_{PL}\vec{f} = (\Delta_{PL}f_0, \Delta_{PL}f_1, \Delta_{PL}f_2) \quad (9)$$

A map  $\vec{f} : M_1 \rightarrow M_2$  is harmonic, if and only if  $\Delta_{PL}\vec{f}$  only has a normal component, and its tangential component is zero.

$$\Delta_{PL}(\vec{f}) = (\Delta_{PL}\vec{f})^\perp \quad (10)$$

## III. STEEPEST DESCENT ALGORITHM

Suppose we would like to compute a mapping  $\vec{f} : M_1 \rightarrow M_2$  such that  $\vec{f}$  minimizes a string energy  $E(\vec{f})$ . This can be solved easily by the steepest descent algorithm:

$$\frac{d\vec{f}(t)}{dt} = -\Delta\vec{f}(t) \quad (11)$$

$\vec{f}(M_1)$  is constrained to be on  $M_2$ , so  $-\Delta\vec{f}$  is a section of  $M_2$ 's tangent bundle.

Specifically, suppose  $\vec{f} : M_1 \rightarrow M_2$ , and denote the image of each vertex  $v \in K_1$  as  $\vec{f}(v)$ . The normal on  $M_2$  at  $\vec{f}(v)$  is  $\vec{n}(\vec{f}(v))$ . Define the normal component as

**Definition 9:** The normal component

$$(\Delta\vec{f}(v))^\perp = \langle \Delta\vec{f}(v), \vec{n}(\vec{f}(v)) \rangle \vec{n}(\vec{f}(v)), \quad (12)$$

where  $\langle \cdot, \cdot \rangle$  is the inner product in  $R^3$ .

**Definition 10:** The absolute derivative is defined as

$$D\vec{f}(v) = \Delta\vec{f}(v) - (\Delta\vec{f}(v))^\perp \quad (13)$$

Then equation (14) is  $\delta\vec{f} = -D\vec{f} \times \delta t$ .

## IV. CONFORMAL SPHERICAL MAPPING

Suppose  $M_2$  is  $S^2$ , then a conformal mapping  $\vec{f} : M_1 \rightarrow S^2$  can be constructed by using the steepest descent method. The major difficulty is that the solution is not unique but forms a Möbius group.

**Definition 11:** Mapping  $f : \mathcal{C} \rightarrow \mathcal{C}$  is a Möbius transformation if and only if

$$f(z) = \frac{az + b}{cz + d}, \quad a, b, c, d \in \mathcal{C}, ad - bc \neq 0, \quad (14)$$

where  $\mathcal{C}$  is the complex plane.

All Möbius transformations form the Möbius transformation group. In order to determine a unique solution we can add different constraints. In practice we use the following two constraints: the zero mass-center constraint and a landmark constraint.

**Definition 12:** Mapping  $\vec{f} : M_1 \rightarrow M_2$  satisfies the zero mass-center condition if and only if

$$\int_{M_2} \vec{f} d\sigma_{M_1} = 0, \quad (15)$$

where  $\sigma_{M_1}$  is the area element on  $M_1$ .

All conformal maps from  $M_1$  to  $S^2$  satisfying the zero mass-center constraint are unique up to the Euclidean rotation group (which is 3 dimensional). We use the Gauss map as the initial condition.

**Definition 13:** A Gauss map  $N : M_1 \rightarrow S^2$  is defined as

$$N(v) = \vec{n}(v), v \in M_1, \quad (16)$$

where  $\vec{n}(v)$  is the normal at  $v$ .

**Algorithm 1:** Spherical Tuette Mapping

Input (mesh  $M$ , step length  $\delta t$ , energy difference threshold  $\delta E$ ), output( $\vec{t} : M \rightarrow S^2$ ) where  $\vec{t}$  minimizes the Tuette energy.

- 1) Compute Gauss map  $N : M \rightarrow S^2$ . Let  $\vec{t} = N$ , compute Tuette energy  $E_0$ .
- 2) For each vertex  $v \in M$ , compute Absolute derivative  $D\vec{t}$ .
- 3) Update  $\vec{t}(v)$  by  $\delta\vec{t}(v) = -D\vec{t}(v)\delta t$ .
- 4) Compute Tuette energy  $E$ .
- 5) If  $E - E_0 < \delta E$ , return  $\vec{t}$ . Otherwise, assign  $E$  to  $E_0$  and repeat steps 2 through to 5.

Because the Tuette energy has a unique minimum, the algorithm converges rapidly and is stable. We use it as the initial condition for the conformal mapping.

**Algorithm 2:** Spherical Conformal Mapping

Input (mesh  $M$ , step length  $\delta t$ , energy difference threshold  $\delta E$ ), output( $\vec{h} : M \rightarrow S^2$ ). Here  $\vec{h}$  minimizes the harmonic energy and satisfies the zero mass-center constraint.

- 1) Compute Tuette embedding  $\vec{t}$ . Let  $\vec{h} = \vec{t}$ , compute Tuette energy  $E_0$ .
- 2) For each vertex  $v \in M$ , compute the absolute derivative  $D\vec{h}$ .
- 3) Update  $\vec{h}(v)$  by  $\delta\vec{h}(v) = -D\vec{h}(v)\delta t$ .
- 4) Compute Möbius transformation  $\vec{\varphi}_0 : S^2 \rightarrow S^2$ , such that

$$\Gamma(\vec{\varphi}) = \int_{S^2} \vec{\varphi} \circ \vec{h} d\sigma_{M_1}, \vec{\varphi} \in \text{Mobius}(CP^1) \quad (17)$$

$$\vec{\varphi}_0 = \min_{\vec{\varphi}} \|\Gamma(\vec{\varphi})\|^2 \quad (18)$$

where  $\sigma_{M_1}$  is the area element on  $M_1$ .  $\Gamma(\vec{\varphi})$  is the mass center,  $\vec{\varphi}$  minimizes the norm in the mass center condition.

- 5) compute the harmonic energy  $E$ .
- 6) If  $E - E_0 < \delta E$ , return  $\vec{t}$ . Otherwise, assign  $E$  to  $E_0$  and repeat step 2 through to step 6.

Step 4 is non-linear and expensive to compute. In practice we use the following procedure to replace it:

- 1) Compute the mass center  $\vec{c} = \int_{S^2} \vec{h} d\sigma_{M_1}$ ;
- 2) For all  $v \in M$ ,  $\vec{h}(v) = \vec{h}(v) - \vec{c}$ ;
- 3) For all  $v \in M$ ,  $\vec{h}(v) = \frac{\vec{h}(v)}{\|\vec{h}(v)\|}$ .

This approximation method is good enough for our purpose. By choosing the step length carefully, the energy can be decreased monotonically at each iteration.

## V. OPTIMIZE THE CONFORMAL PARAMETERIZATION BY USING LANDMARKS

In order to compare two brain surfaces, it is desirable to adjust the conformal parameterization and match the geometric features on the brains as well as possible. We define an energy to measure the quality of the parameterization. Suppose two brain surfaces  $S_1, S_2$  are given, conformal parameterizations are denoted as  $f_1 : S^2 \rightarrow S_1$  and  $f_2 : S^2 \rightarrow S_2$ , the *matching energy* is defined as

$$E(f_1, f_2) = \int_{S^2} \|f_1(u, v) - f_2(u, v)\|^2 du dv \quad (19)$$

We can composite a Möbius transformation  $\tau$  with  $f_2$ , such that

$$E(f_1, f_2 \circ \tau) = \min_{\zeta \in \Omega} E(f_1, f_2 \circ \zeta), \quad (20)$$

where  $\Omega$  is the group of Möbius transformations. We use landmarks to obtain the optimal Möbius transformation. Landmarks are commonly used in brain mapping. We manually label the landmarks on the brain as a set of uniformly parametrized sulcal curves [4], as shown in Figure 7. First we conformally map two brains to the sphere, then we pursue an optimal Möbius transformation to minimize the Euclidean distance between the corresponding landmarks on the spheres. Suppose the landmarks are represented as discrete point sets, and denoted as  $\{p_i \in S_1\}$  and  $\{q_i \in S_2\}$ ,  $p_i$  matches  $q_i$ ,  $i = 1, 2, \dots, n$ . The landmark mismatch functional for  $u \in \Omega$  is defined as

$$E(u) = \sum_{i=1}^n \|p_i - u(q_i)\|^2, u \in \Omega, p_i, q_i \in S^2 \quad (21)$$

In general, the above variational problem is a nonlinear one. In order to simplify it, we convert it to a least squares problem. First we project the sphere to the complex plane, then the Möbius transformation is represented as a complex linear rational formula, Equation 14. We add another constraint for  $u$ , so that  $u$  maps infinity to infinity. That means the north poles of the spheres are mapped to each other. Then  $u$  can be represented as a linear form  $az + b$ . Then the functional of  $u$  can be simplified as

$$E(u) = \sum_{i=1}^n g(z_i)|az_i + b - \tau_i|^2 \quad (22)$$

where  $z_i$  is the stereo-projection of  $p_i$ ,  $\tau_i$  is the projection of  $q_i$ ,  $g$  is the conformal factor from the plane to the sphere, it can be simplified as

$$g(z) = \frac{4}{1 + z\bar{z}}. \quad (23)$$

So the problem is a least squares problem.

## VI. SPHERICAL HARMONIC ANALYSIS

Let  $L^2(S^2)$  denote the Hilbert space of square integrable functions on the  $S^2$ . In spherical coordinates,  $\theta$  is taken as the polar (colatitudinal) coordinate with  $\theta \in [0, \pi]$ , and  $\phi$  as the azimuthal (longitudinal) coordinate with  $\phi \in [0, 2\pi]$ . The usual inner product is given by

$$\langle f, h \rangle = \int_0^\pi \left[ \int_0^{2\pi} f(\theta, \phi) \overline{h(\theta, \phi)} d\phi \right] \sin \theta d\theta.$$

A function  $f : S^2 \rightarrow \mathbb{R}$  is called a *Spherical Harmonic*, if it is an eigenfunction of Laplace-Beltrami operator, namely  $\Delta f = \lambda f$ , where  $\lambda$  is a constant. There is a countable set of spherical harmonics which form an orthonormal basis for  $L^2(S^2)$ .

For any nonnegative integer  $l$  and integer  $m$  with  $|m| \leq l$ , the  $(l, m)$ -spherical harmonic  $Y_l^m$  is a harmonic homogeneous polynomial of degree  $l$ . The harmonics of degree  $l$  span a subspace of  $L^2(S^2)$  of dimension  $2l + 1$  which is invariant under the rotations of the sphere. The expansion of any function  $f \in L^2(S^2)$  in terms of spherical harmonics can be written

$$f = \sum_{l \geq 0} \sum_{|m| \leq l} \hat{f}(l, m) Y_l^m$$

and  $\hat{f}(l, m)$  denotes the  $(l, m)$  Fourier coefficient, equal to  $\langle f, Y_l^m \rangle$ . Spherical harmonic  $Y_l^m$  has an explicit formula

$$Y_l^m(\theta, \phi) = k_{l,m} P_l^m(\cos \theta) e^{im\phi},$$

where  $P_l^m$  is the associated Legendre function of degree  $l$  and order  $m$  and  $k_{l,m}$  is a normalization factor. The details are explained in [20].

Once the brain surface is conformally mapped to  $S^2$ , the surface can be represented as three spherical functions,  $x^0(\theta, \phi), x^1(\theta, \phi)$  and  $x^2(\theta, \phi)$ . The function  $x^i(\theta, \phi) \in L^2(S^2)$  is regularly sampled and transformed to  $\hat{x}^i(l, m)$  using Fast Spherical Harmonic Transformation as described in [21].

Many processing tasks that use the geometric surface of the brain can be accomplished in the frequency domain more efficiently, such as geometric compression, matching, surface denoising, feature detection, and shape analysis [22], [23].

### A. Brain Geometry Compression

Similar to image compression using Fourier analysis, geometric brain data can be compressed using spherical harmonic analysis [22]. Global geometric information is concentrated in the low frequency components, whereas noise and locally detailed information is concentrated in the high frequency part. By using low pass filtering, we can keep the major geometric features and compress the brain surface without losing too much information.

### B. Rotation Invariant Shape Descriptor

The geometric representation  $(x^1(\theta, \phi), x^2(\theta, \phi), x^3(\theta, \phi))$  depends on the orientation of the brain. Brain registration has to be applied first in order to compare the geometric representations of two different brains. A rotation-invariant shape descriptor can be formulated based on the frequency

coefficients. Because the harmonics of degree  $l$  span the rotation invariant subspace of  $L^2(S^2)$ , the following shape descriptor is also rotation invariant

$$s(l) = \sum_i \sum_{|m| \leq l} \|\hat{x}^i(l, m)\|^2. \quad (24)$$

Given two brain surfaces, we can compute their shape descriptor from their spherical harmonic spectrum, and compare them directly without any registration.

Figure 10 illustrate the shape descriptors for the same brain with different orientations. It is clear that the shape descriptor is totally rotation invariant [24].

Spherical harmonic analysis can be applied to brain surface denoising and feature extraction also. In order to compare two brain surfaces, it can be more efficient to compare their low band frequency coefficients.

## VII. EXPERIMENTAL RESULTS

The 3D brain meshes are reconstructed from 3D 256x256x124 T1 weighted SPGR (spoiled gradient) MRI images, by using an active surface algorithm that deforms a triangulated mesh onto the brain surface [5]. Figure 3(a) and (c) show the same brain scanned at different times [4]. Because of the inaccuracy introduced by scanner noise in the input data, as well as slight biological changes over time, the geometric information is not exactly the same. Figure 3(a) and (c) reveal minor differences.

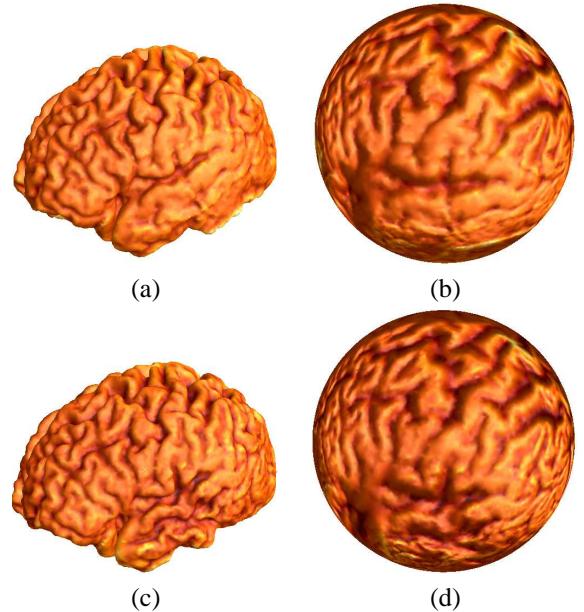


Fig. 3. Reconstructed brain meshes and their spherical harmonic mappings. (a) and (c) are the reconstructed surfaces for the same brain scanned at different times. Due to scanner noise and inaccuracy in the reconstruction algorithm, there are visible geometric differences. (b) and (d) are the spherical conformal mappings of (a) and (c) respectively; the normal information is preserved. By the shading information, the correspondence is illustrated.

The conformal mapping results are shown in Figure 3(b) and (d). From this example, we can see that although the brain meshes are slightly different, the mapping results look quite similar. The major features are mapped to the same position

on the sphere. This suggests that the computed conformal mappings continuously depend on the geometry, and can match the major features consistently and reproducibly. In other words, conformal mapping may be a good candidate for a canonical parameterization in brain mapping.

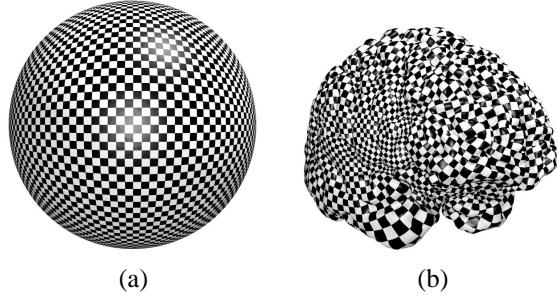


Fig. 4. Conformal texture mapping. (a) Texture mapping of the sphere; (b) Texture mapping of the brain. The conformality is visualized by texture mapping of a checkerboard image. The sphere is mapped to the plane by stereographic projection, then the planar coordinates are used as the texture coordinates. This texture parameter is assigned to the brain surface through the conformal mapping between the sphere and the brain surface. All the right angles in the texture are preserved on the brain surface.

Figure 4 shows the mapping is conformal by texture mapping a checkerboard to both the brain surface mesh and a spherical mesh. Each black or white square in the texture is mapped to sphere by stereographic projection, and pulled back to the brain. Note that the right angles are preserved both on the sphere and the brain.

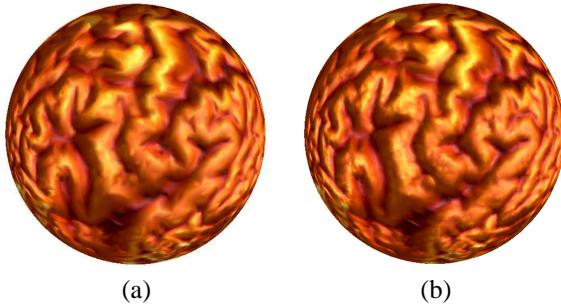


Fig. 5. Conformal mappings of surfaces with different resolutions. (a).Surface with 20,000 faces; (b) Surface with 50,000 faces. The original brain surface has 50,000 faces, and is conformally mapped to a sphere, as shown in (a). Then the brain surface is simplified to 20,000 faces, and its spherical conformal mapping is shown in (b).

Conformal mappings are stable and depend continuously on the input geometry but not on the triangulations, and are insensitive to the resolutions of the data. Figure 5 shows the same surface with different resolutions, and their conformal mappings. The mesh simplification is performed using a standard method. The refined model has 50k faces, coarse one has 20k faces. The conformal mappings map the major features to the same positions on the spheres.

In order to measure the conformality, we map the iso-polar angle curves and iso-azimuthal angle curves from the sphere to the brain by the inverse conformal mapping, and measure the intersection angles on the brain. The distribution of the angles of a subject (A) are illustrated in Figure 6. The angles are concentrated about the right angle.

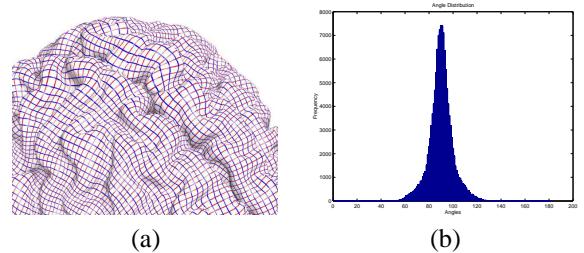


Fig. 6. Conformality measurement. (a) Intersection angles; (b) Angle distribution. The curves of iso-polar angle and iso-azimuthal angle are mapped to the brain, and the intersection angles are measured on the brain. The histogram is illustrated.

Subject	Vertex #	Face #	Before	After
A	65,538	131,072	-	-
B	65,538	131,072	604.134	506.665
C	65,538	131,072	414.803	365.325

TABLE I  
MATCHING ENERGY FOR THREE SUBJECTS. SUBJECT A WAS USED AS THE TARGET BRAIN. FOR SUBJECTS B AND C, WE FOUND MÖBIUS TRANSFORMATIONS THAT MINIMIZED THE LANDMARK MISMATCH FUNCTIONS, RESPECTIVELY.

Figure 7 shows the landmarks, and the result of the optimization by a Möbius transformation. We also computed the matching energy, following Equation 19. We did our testing on three example subjects. Their information is shown in Table I. We took subject A as the target brain. For each new subject model, we found a Möbius transformation that minimized the landmark mismatch energy on the maximum intersection subsets of it and A. As shown in Table I, the matching energies were reduced after the Möbius transformation.

Figure 8 illustrates the geometric compression results using spherical harmonic compression. Figure 9 shows the  $L^2$  errors of the compression result. The low pass filters are applied to remove high frequency components, and the surfaces are reconstructed from the remaining low frequency components. The surface is normalized such that the total area is  $4\pi$ , then the  $L^2$  error between the reconstructed surface and the original surface is computed. The curve shows the normalized  $L^2$  error vs the ratio of retained low frequency components. The figure illustrates that the major geometric information is encoded in the low frequency part.

Figure 10 illustrates the relative error between the rotation-invariant shape descriptors for the original brain surface and for the rotated brain surface. Because the first 30 low frequency components generate more than 99% of the total energy, only the first 30 shape descriptor errors are shown in the figure. From the figure, it is clear that the relative errors are less than one percent, and therefore the shape descriptors are rotation invariant.

The method described in this work is quite general. We tested the algorithm on other genus zero surfaces, including the hand and foot surface. Some of the experimental results are illustrated in Figure 11.

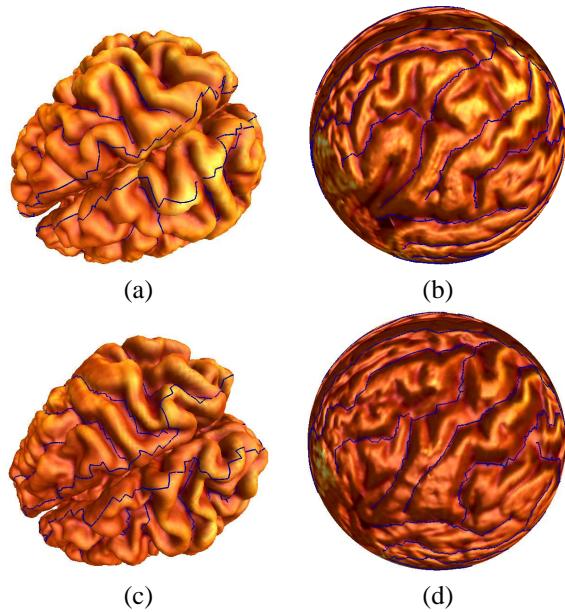


Fig. 7. Möbius transformation to minimize the deviations between landmarks. The blue curves are the landmarks. The correspondence between curves has been preassigned. The desired Möbius transformation is obtained to minimize the matching error on the sphere.

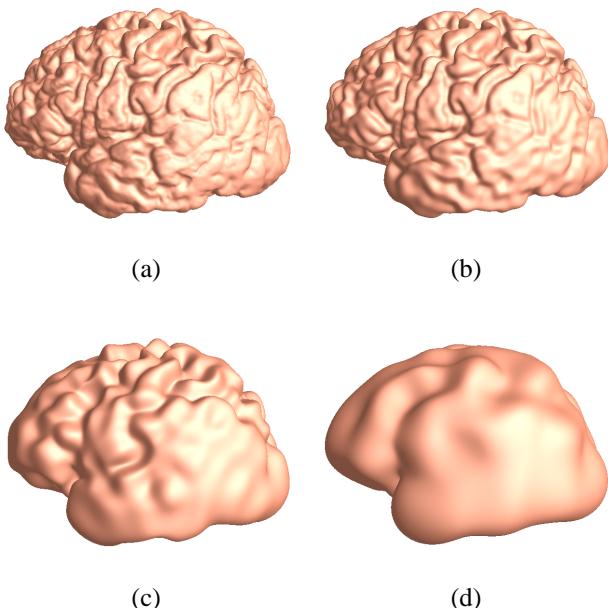


Fig. 8. This figure illustrates the geometric compression results using spherical harmonics. After we conformally map the brain to a sphere, we can use spherical harmonics to compress the geometry. (a) is the original brain surface. (b), (c) and (d) are brain surfaces reconstructed from spherical harmonics with  $\frac{1}{8}$ ,  $\frac{1}{64}$  and  $\frac{1}{256}$  of the original low frequency coefficients, separately.

## VIII. COMPARISON WITH OTHER WORK

Several other studies of conformal mappings between brain surfaces are reported in [2], [3], [15], [17]. In [2], [17], Hurdal et al. used the circle packing theorem and the ring lemma to establish a theorem: there is a unique circle packing in the plane (up to certain transformations) which is quasi-conformal (i.e. angular distortion is bounded) for a simply-connected triangulated surface. They demonstrated their experimental results for the surface of the cerebellum. This method only considers the topology without considering the brain's geometric structure. Given two different mesh structures of the same brain, one can predict that their methods may generate two different mapping results. Compared with their work, our method really preserves angles and establishes a good mapping between brains and a canonical space.

Haker et al. [3], [15] built a finite element approximation of the conformal mapping method for brain surface parameterization. They selected a point as the north pole and conformally mapped the cortical surface to the complex plane. In the resulting mapping, the local shape is preserved and distances and areas are only changed by a scaling factor. Based on Haker et al. [3], Joshi et al. [25] obtained a unique conformal mapping by fixing three point correspondences between two brains. Since stereo projection is involved, there is significant distortion around the north pole areas, which brings instability to this approach. Compared with their work, our method is more accurate, with no regions of large area distortion. It is also more stable and can be readily extended to compute maps between two general manifolds.

Finally, we note that Memoli et al. [26] mentioned they were developing implicit methods to compute harmonic maps between general source and target manifolds. They used level sets to represent the brain surfaces. Due to the extensive folding of the human brain surface, these mappings have to be designed very carefully.

## IX. CONCLUSION AND FUTURE WORK

In this paper, we propose a general method which finds a unique conformal mapping between genus zero manifolds. Specifically, we demonstrate its feasibility for brain surface conformal mapping research. Our method only depends on the surface geometry and not on the mesh structure (i.e. gridding) and resolution. Our algorithm is efficient and stable

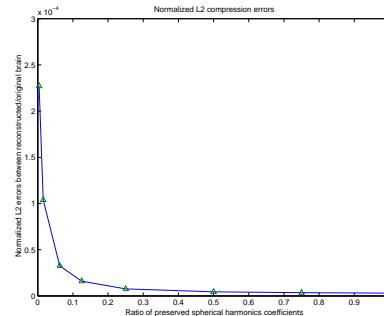


Fig. 9. This figure illustrates the normalized  $L^2$  errors of the compression.

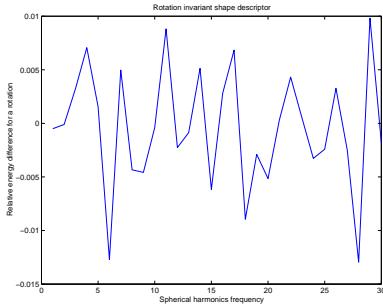


Fig. 10. The brain surface is rotated 90 degree with respect to x-axis. The shape descriptors defined in 24 are computed for both the original surface and the rotated surface, denoted as  $s(l)$  and  $s'(l)$  respectively. The relative errors  $(s(l) - s'(l))/s(l)$  is illustrated as a function of  $l$ . Because the first 30  $s(l)$  generate almost all the energy, the curve is truncated at  $l = 30$ . From the curve it can be verified that the relative error is less than one percent, and thus the shape descriptors are rotation invariant.

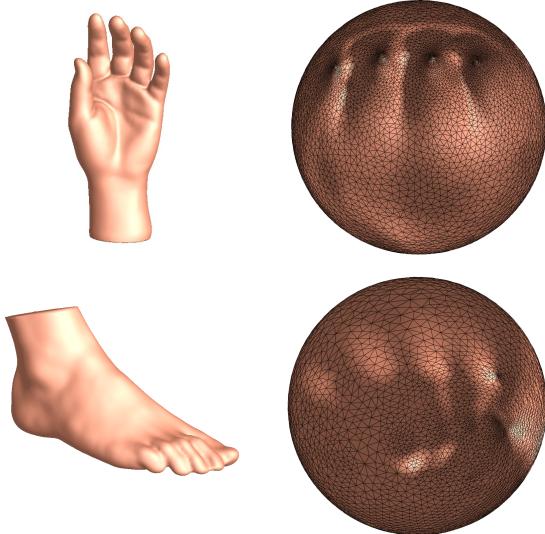


Fig. 11. Spherical conformal mapping of genus zero surfaces. Extruding parts (such as fingers and toes) are mapped to denser regions on the sphere.

in reaching a solution. Landmark information are integrated to optimize the brain surface conformal parameterization. We apply conformal mapping to the brain surface spherical harmonic transformation, which is used for geometry compression and rotation-invariant shape analysis. In the future research, we will study several applications of these mapping algorithms, such as providing a canonical space for automated feature identification, brain to brain registration, brain structure segmentation, brain surface denoising, shape analysis and convenient surface visualization, among others. We are trying to generalize this approach to compute conformal mappings between non-zero genus surfaces.

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