Research Statement

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I am conducting my research at Center of Visual Computing (CVC) of Stony Brook University, which is one of the best visual computing research centers in the world. My broad research interests lie in computer graphics, geometric and physically-based modeling, medical imaging, computer animation/simulation, visualization, computer vision, and human-computer interaction. During the past three years, I focus my dissertation research on studying relationship (more specifically, matching) between geometric shapes including curves, surfaces and solids, and I have also worked on their various applications in graphics, modeling, medical imaging and visualization fields.

1 Summary of Dissertation Research

Proliferation of 3D digital photographic and scanning devices and shape modeling techniques boosts the number of available high quality 3D geometric digital models. As a result, the need to the ability of making good use of existing models has gained the prominence. A key concern of computer graphics and shape modeling is shifting to effectively understanding, retrieving and reusing models in database. In order to measure and analyze difference among existing digital models, people need to compute registration between given objects. Rigorously speaking, they find good one-to-one correspondence between points on objects. Inter-Shape matching and comparison are important and challenging topics with great potentials because they serve directly for many applications in broad fields of graphics, vision, visualization and modeling. My dissertation research focuses on this problem as well as its various applications. I focus on computing maps between surfaces or volumetric data because they are most related to our daily digital models.

In current geometric processing pipeline of computer graphics, vision and modeling fields, digital models are mostly represented using their boundary surfaces. Surface mapping therefore remains to be a fundamental and central problem in these fields. My study of surface matching starts from reducing the problem by one dimension. I study curves on surfaces because curves on surfaces convey large amount of information of their embedded surfaces (Section 1.1 and [5]). We design signatures (finger prints) for curves on surfaces to measure their differences. Furthermore, based on this, we match segmentations of two surfaces, and compose sub-mappings between corresponding sub-regions to a global result.

The above idea of converting global surface mapping into subregions mapping is a predominant approach of states-of-the-art techniques for mapping general surfaces. However, existing techniques usually require heavy user intervention or even manual design for consistent segmentations between matched surfaces. This prevents the automatic mapping computation. Eliminating case-by-case user involvements is critical in performing registration for many digital data. Towards this goal, we design a canonical decomposition framework so that surfaces with arbitrary topology can be automatically and consistently segmented for the mapping computation (see Section 1.2 and [6]).

We also rigorously study distortions of surface mappings and present a global optimization algorithm so that global convergence to the unique stretching-minimized map is guaranteed (see Section 1.3 and [4]). This is the first work towards rigorously computing the global stretching-minimized map between surfaces with non-trivial topology.

Registering volumetric data has great applications in medical and simulation fields. In reality, we may want to consider not only shell of an object but also its interior materials. Therefore, we extend the study of shape mapping from surfaces to solid objects (see Section 1.4 and [7]). We design an effective algorithm to compute the harmonic volumetric map between two solid shapes, so that not only surface points on the shell of the object, but also the interior points are registered. We demonstrate the result as well as the strong potential of volumetric mapping using many valuable applications.

1.1 Curve Signature and its Application for Surface Matching

We design a signature to uniquely identify each simple closed curve laid on a genus-zero surface. To our best knowledge, this is the first work towards a rigorous classification for curves on surfaces: a signature uniquely represents a curve on the surface and it can be used to reconstruct this curve. This signature characterizes the relationship between the curve and its embedded surface; in other words, it measures how the curve segments the surface. Therefore, we use it to match segmentations of two surfaces, and
we present a shape mapping framework based on segmentation guided by curve signatures matching. We apply our method on human faces and brain cortices matching. The segmentation of a genus-zero surface can be transferred to the second surface, so that a semi-automatic matching between genus-zero surfaces can be computed.

1.2 Surface Matching with Pants Decomposition

Current state-of-the-art surface mapping techniques usually segment complicated surfaces into subregions and then compose matching of subregion pairs to get the global inter-surface map. Many of them focus on handling surfaces with trivial topology. Techniques for high genus surfaces usually rely on heavy user interventions. We present a powerful decomposition framework for surfaces with arbitrary topology types. Surfaces even with different topology can be automatically matched with almost no user involvement. On the other hand, it also flexibly handles the semantics requirements from users by allowing feature points/curves matching when user control is preferred.

1.3 Globally Optimal Surface Matching

Current surface mapping techniques lack of rigorous math foundation and do not guarantee the optimality of the global mapping distortion. With solid mathematic advance on hyperbolic geometry and Riemmanian Uniformization theorem, we present an iterative algorithm that guarantees to reach a globally optimal mapping between two given surfaces with non-trivial topology. We prove our algorithm converges to the globally unique result with minimized stretching energy. This surface mapping generates between surfaces a physically natural one-to-one correspondence with low angular distortion. It can be used for various applications such as texture transfer, morphing, shape matching and so on.

1.4 Harmonic Volumetric Mapping

We generalize our mapping problem from 2D surfaces to 3D volumetric data. This work presents a simple and effective volume mapping technique to generate point-to-point correspondence between two solid objects. We convert the harmonic volumetric mapping computation to a set of elliptic partial differential equations; and
we bring into this field an efficient boundary method called the fundamental solution method. Compared with existing techniques, the 3D volumetric mapping problem now is reduced by one dimension because only the boundary condition is considered, therefore the computational complexity has been greatly reduced. The algorithm computes a harmonic volumetric map between two solid objects, and we demonstrate the result as well as its great potential by many real applications, including volumetric information transfer, tetrahedral remeshing, and solid texture synthesis. We also use such a volumetric registration result for solid objects comparison and analysis.

2 Future Research Plan

Based on my research experiences at Stony Brook University and my expertise in shape mapping, geometric modeling/processing, differential geometry, partial differential equations, computational geometry/topology and physically based simulation, I will continue my efforts of exploring the shape mapping computation problems from theoretical aspects, designing and improving efficient numerical algorithms, and searching for its new applications as well as interdisciplinary collaboration possibility. In the interest of space, here I will only discuss a few problems directly extended from my dissertation research. They are fundamental and interesting, and will constitute my research directions in the near future.

2.1 Shape Retrieval based on Shape Mapping

Shape comparison and retrieval from shape database (for either surfaces or solid objects) remains to be an important and hot topic in graphics and vision fields. Since we are able to automatically compute the low distorted registration between any two given shapes, we can subtract them in a meaningful way. Also, we design different shape comparison metrics according to different applications. For example, to design a pose-oblivious comparison, i.e., focus on stretching and ignore the bending, we only integrate the difference of the area stretching tensor upon the shape; to design comparison that differentiates bending difference, we can further consider the curvature difference. I am interested in applying shape comparison and retrieval for real data in fields such as biometrics, such as human faces matching and retrieval. With the technology advance of high-resolution, real-time 3D shape acquisition system based on structured light or holographic techniques, real-time shape registration and comparison will demonstrate its significance in biometrics and homeland security. Our delicate registration technique will definitely benefit the comparison and recognition in these areas.

2.2 Medical Imaging, Medical Data Matching and Analysis

Registration of medical data such as reconstructed surface or volumetric MRI data is a one of the core research topics in medical imaging. Low-distorted shape (surface/volume) mapping directly provides us a powerful registration of data that we want to match. Based on our advance on surface mapping, I would like to find collaboration with vision/medical imaging people, and extem my previous work on cortex matching [3] from the closed genus zero case to more general cases so that real deforming clinic data can be tracked and analyzed. It is also inspiring to explore the application of volumetric mapping on MIR data. The evolution of organic data such as heart or brain can be registered and matched using our volumetric mapping. This provides a powerful tool for detecting the pathological changes of these organs.

2.3 Medical Data Visualization and Virtual Surgery

Shape mapping also gives us a powerful platform and tool for visualizing medical data. For example, reconstructed organic surface data such as brain cortex surface is usually very convoluted in $\mathbb{R}^3$ space, directly visualizing it is difficult. Since we can unfold these kind of organ surfaces to flatten canonical domains such as sphere or cubes, and the mapping is with low distortion (i.e. the local shape is well preserved [3]); we are able to visualize it effectively. For volumetric data, the similar concept works, with the mapping, we can easily visualize different layers of interior region of the object through arbitrary cross-sections on the canonical domain shape.

If the shape mapping between a real object to a canonical shape domain has been computed, the physically-based simulation can be performed efficiently on the canonical domain (as discussed in our previous work [2]). This greatly reduces the computation complexity compared to performing the simulation on directly on original objects. I am looking forward to collaboration opportunities with people with visualization or medical imaging backgrounds and explore along this direction. I believe this can benefit the real time simulation for virtual surgery, and it will serve greatly for surgical trainings/educations.

2.4 Tetrahedral Remeshing

Generating regular tetrahedral meshes has great importance in mechanical engineering and CAD fields. A solid object with hexahedral structure is highly desirable for finite element analysis and physically-based simulations. This is because such a regular hexahedral structure provides great precision and efficiency for geometry processing and
physically based computation. I plan to explore my current work on this topic [7] further; with a “progressive tetrahedral mesh” and local iterative adjustment, the computational efficiency and the hexahedral-mesh quality can be further improved.

2.5 Shape Database, Modeling from Examples

A key concern of computer graphics and shape modeling is to effectively reuse models or parts in database. I plan to work on this direction based on our surface decomposition framework. Since our algorithm [6] canonically decomposes a surface into a set of patches with “pants” topology (a topological sphere with three holes). We should be able to streamline “cut-and-paste” operation along the pants’ holes, and generate more meaningful shapes using existing example sub-patches in the “parts” database. I also plan to generalize our pants decomposition concept solid models so that the “modeling by example” pipeline can be processed on database with solid objects.

2.6 Dynamic Data Modeling and Deformation Transfer

The registration between two objects can benefit not only the static data, but also the modeling of dynamic data. With the mapping between two objects, we can transfer not only the static information such as texture, density, material etc., but also dynamic information such as deformation gradient tensor. Therefore, when the deformation of one object has been computed, we can transfer its deformation gradient tensor to cologne its deformation behavior on the target object.

Much research work has been conducted to reuse the existing deformation sequence of one articulated object by transferring this deformation to other objects. On the other hand, harmonic volumetric mapping can simplify the deformation generation for complicated objects. If we get the correspondence between a complicated object and a simple and canonical shape domain, then we can reduce the computational complexity of the object’s deformation by performing it on the simplified shape domain (like free-form deformation but we provide refiner control on all boundary points as well as interior feature points).

2.7 Other Applications

I am looking for more applications and collaboration opportunities based on my current work. Some potential directions are as follows. First, it can serve for spline constructions. Splines are built upon an estimation domain. And it requires the underlying mapping to be low distorted and globally continuous. Our globally optimal surface mapping is an ideal choice for this purpose. Second, mapping between objects and some canonical domain provides us a canonical storage for these objects. This may lead to possible digital data compression. For example, I plan to apply volumetric mapping from objects polycubes for generating a volumetric geometry image.

2.8 Long Term Research Plan

In the long term, I would like to work towards designing automatic and efficient shape retrieval engines. I am also interested in exploring other possible mapping techniques that can improve the shape mapping effects. Combining my work with machine learning is an inspiring direction. Also, our current shape mapping is based on geometry, combining it with psychopathology knowledge, molecular structure knowledge, and so on could definitely broaden its practical applications.

References