Digital Geometry Processing

1. Research Team

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2. Statement of Project Goals

The multimedia revolution has encompassed three types of data so far: sound, image, and video. The goal of this proposal is to establish an entirely new and much needed research area: **Digital Geometry Processing** (DGP). Its goal is the research of mathematical and computational foundations needed for the next wave of multimedia data: geometry. Unlike previous data types, we cannot rely on existing theoretical and algorithmic tools since geometric data has intrinsic properties, such as topology, curvature, and non-uniform sampling that render most traditional tools useless. The distinction to the previous three waves of multimedia is fundamental and cannot be overcome by simple adaptation of existing machinery.

We plan to develop theoretical and algorithmic foundations for efficient, reliable and scalable tools for acquisition, coding, transmission, enhancement, editing, authentication, simulation and many other types of DGP operations. This will provide a complete mesh processing pipeline to allow for easy and efficient manipulation of this new data type. The research team, in collaboration with others universities (Caltech, NYU, Rice U., UoW) and with a wealth of experience and substantial achievements in related areas, is making rapid progress towards this ambitious goal.

3. Project Role in Support of IMSC Strategic Plan

This research contributes to the general IMSC vision by allowing the next wave of multimedia data, **3D geometry**, to be transmitted efficiently on the web. Interactions with the rest of IMSC are mainly centered on our graphics expertise, for both hardware and software. Research on geometry processing will directly benefit the IMSC strategic plan as it promises to be extremely rewarding in terms of both educational and societal impacts. It will create a generation of researchers and professionals, with deep understanding of the diverse techniques from geometric modeling, computer graphics, signal processing, approximation theory and differential geometry required to advance the state of the art in digital geometry processing. Previous advances in digital signal processing (DSP), which formed the foundation of the first three waves of multimedia, are changing our society in many ways. From cellular phones to HDTV, scientific and technological progress in signal processing has led to successful industrial applications with substantial societal impact. The growth of digital geometry processing applications will similarly impact many areas of human activity, from entertainment to engineering, science and medicine.

4. Discussion of Methodology Used

This project aims to bring the understanding of computational representations for 3D geometry to the level that currently exists for sound, images, or movies. We will approach this challenge by advancing a number of *fundamental theoretical tools*. We regard the development of the basic mathematical foundations as essential to the overall design of DGP tools. Some of the directions we plan to pursue contribute directly to the **creation of more robust and scalable algorithms**; others are needed to **improve our general understanding of geometric sampling.**

Sampling theory for surfaces: The importance of developing a basic sampling theory that takes into account distinctive characteristics of geometric data is clear from the discussion in the two previous sections. Ideally, we would like to develop analogs of Shannon's theorem for geometric data.

Approximation for surfaces: While the theory of approximation for functions is extremely well developed, little is known about constructive approximations of surfaces by other surfaces. One of our goals is to find adequate mathematical descriptions of such approximations and general approaches to estimate the rate of convergence for such approximations.

Discrete differential-geometry operators: Having discrete versions of standard differential geometry quantities is necessary for reasoning about sampled geometry. Finite differences are a convenient way to compute local differential operators on regular 1D, 2D, or 3D grids. On arbitrary meshes however, we need to find equivalent formulations that provide local discrete approximations of conventional continuous operators while ensuring numerical accuracy (the left of Figure 2 shows an example of smoothing performed through an appropriate discretization of the Laplace-Beltrami operator). These discrete operators must also satisfy global properties for any topology, such as the Gauss-Bonnet theorem, which makes their design subtler than in Euclidean spaces.

Irregular meshes: One often does not have control over the acquisition process and the output of many acquisition algorithms is an irregular (triangle) mesh. Irregular refers to the fact that vertices may have any number of neighbors. In such meshes parameter information and geometry are intricately intertwined.

- Geometric and topological denoising: Much acquired geometry needs to be denoised geometrically [9,30] and topologically. The latter aspect has received almost no attention; however, geometric acquisition errors can lead to topological errors. We will study ``topology denoising'' as well as sampling criteria to guarantee topology.

- Parameterization: The irregular connectivity and shape of triangles must be taken carefully into account [9,13,15,25] when discretizing operators. Alternatively one may produce remeshes [16,20], which are semi-regular and come imbued with better analysis tools. We will pursue both approaches.

- Simplification: Hierarchical representations for surfaces can be built upon simplification primitives [14]. We will study manifold preserving, but topology changing simplification as well as error criteria that take into account subsequent processing requirements such as physically faithful simulation.

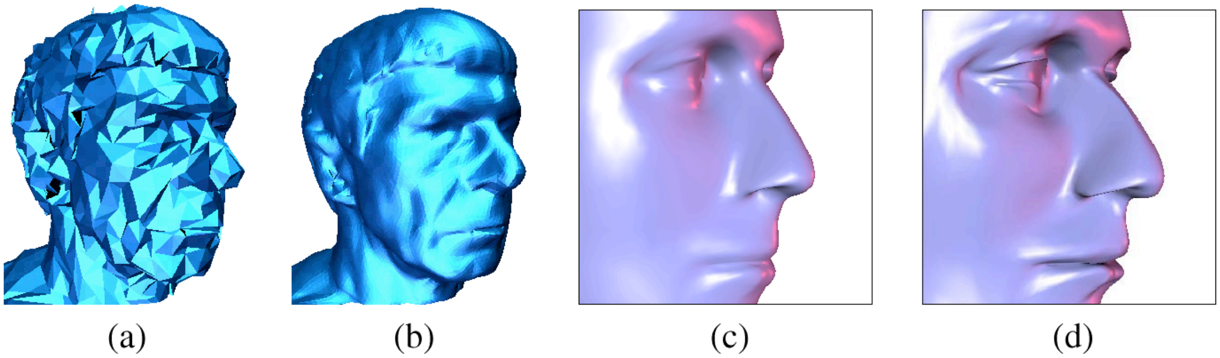

Figure 1: Example of smoothing: (a) and (b); enhancement: (c) and (d) (from [DMSB99]).

Compression: Compression of carefully designed irregular meshes, be they for medical data or collaborative design, is also an important avenue of research. We will make a particular effort to design new 3D compression algorithms with provable bit-rate bounds and simple compressed formats to allow for fast transfer of 3D data across the net.

5. Short Description of Achievements in Previous Years

This research project has been in progress only for three years. During this period, we published results in the field of compression, discrete differential geometry, simulation, and topology analysis [1-3,5-11,19,21,23,26-28,31], leading to several siggraph papers and journal publications.

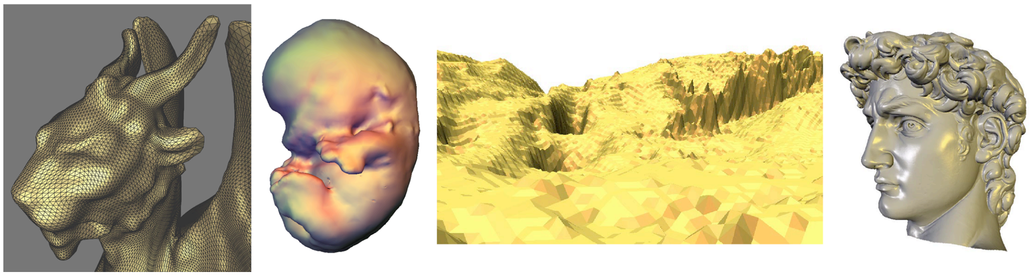

Figure 2: Some meshes resulting from our approach, using medical or scanned data after processing.

5a. Detail of Accomplishments During the Past Year

This past year, we focused both on theoretical and practical advances. First, we studied the **anisotropy** of meshes. Defining the shape operator for discrete meshes has allowed us different applications, depicted in Figure 3: **anisotropic remeshing**, and **thin-shell simulation**. These two contributions represent significant advances, as anisotropy has barely been exploited in graphics, despite important implications for surface compression. Similarly, thin shell simulations are reputed computationally intensive – yet, we proved that a simple, yet accurate model for the shape operator can lead to fast computations and excellent numerical behavior.

We also introduced a new method for **anisotropic smoothing** of large meshes, using robust estimation. This new approach is much faster, while preserving solid foundations that guarantee proper fairing of complex geometry.

Figure 3: Some of our latest results on remeshing, shell animation, medical data compression, and smoothing.

Finally, we continued our effort to produce 3D compression schemes: we proposed an **isosurface compression method** that achieves the current best compression rates. Complex medical data such as skulls or teeth or various organs can be transmitted over the web in only a few kilobytes.

6. Other Relevant Work Being Conducted and How this Project is Different

This research on mesh processing has received a lot of attention in the last two years. In June 2003, a Symposium on Geometry Processing, regrouping the main actors of this research theme, will be held in Germany. Our approach has a unique place among this field in the fact that we propose both theoretical and practical approaches to mesh processing. Instead of developing ad-hoc techniques designed for special meshes, we are dedicated to extend the mathematical techniques and foundations in order to develop general, predictive methods for mesh processing. We are also dedicated to establish strong connections between graphics and applied mathematics, as geometry is a central in a lot of applied sciences.

7. Plan for the Next Year

We plan to further develop this research on Digital Geometry Processing. We plan to both transfer our technology to the industry (to create robust geometry tools) and carefully examine the connections between our work and other fields' advances (such as Mimetic Operators, Discrete Mechanics) since initial discussions with other researchers have shown interests and commonalities between our work and some new results in math, physics, and applied math. We will work towards ubiquitous geometry: with all of the mesh processing pipeline in place, geometry can become common place, such as in 3D camera, PDAs, watches, etc…

8. Expected Milestones and Deliverables

The next expected milestone is the development of a *geometry theory,* a counterpart to signal theory where clear abstraction of signals was defined. It is quite a stretch, as a significant amount of research needs to be achieved to achieve such a milestone, but our recent results seem to indicate that we should be able to reach preliminary results within a year or two. In the meantime, more applications ill become available. Moreover, since the beginning, we put a special emphasis on delivering test programs (available on the web from our site: http://www-grail.usc.edu/), like 3D mesh compression techniques (progressive or single-rate). We plan to continue to share our code with the rest of the community as we finish our projects.

9. Member Company Benefits

Our new techniques are highly relevant for any member company working with geometry, or with geometry-related issues. We offer access to our papers before they get published, and we also provide implementations for evaluation purposes. We are also open to suggestions for research directions, since we like to provide useful contributions, and often, companies know what the main problems are in a field.

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