Report on Interactive Geometry Remeshing: Implementation and Application

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***Abstract*—This document details the development and implementation of a sophisticated mesh remeshing system designed to enhance the interactivity and efficiency of geometry processing tasks. Inspired by pioneering work in interactive geometry remeshing, this project leverages advanced computational techniques to enable dynamic and user-guided remeshing of complex 3D meshes. The core of our system utilizes harmonic parameterization to minimize geometric distortion during mesh flattening, coupled with a detailed curvature analysis to identify regions requiring enhanced sampling. This allows for precision in feature preservation and optimal mesh quality.**

A key contribution of our implementation is the introduction of an interactive control map, derived from the combination of geometric properties and user input, which dictates the density and distribution of mesh sampling. This approach facilitates the creation of customized meshes that cater to specific application requirements, such as computational fluid dynamics and finite element analysis, where mesh uniformity and quality are critical. Furthermore, we employ a novel halftoning technique for mesh sampling which respects the designated control map, ensuring that high-priority regions are sampled more densely to preserve essential geometric features.

The system demonstrates significant improvements in mesh processing speed and interactivity, enabling real-time user feedback and adjustments. This capability significantly enhances productivity and flexibility in mesh generation, offering a practical solution to the often time-consuming task of mesh optimization in commercial and research applications. The results of our implementation showcase not only the technical feasibility of combining several advanced geometric processing techniques but also their practical applicability in improving the quality and utility of 3D meshes.

***Index Terms*—Mesh remeshing, geometry processing, curvature analysis, harmonic parameterization, interactive systems**

I. Introduction

The need for high-quality mesh models is prevalent in fields ranging from computer graphics to computational engineering. This project implements a mesh remeshing system that allows for interactive adjustments and optimizations, significantly enhancing the utility and flexibility of geometric models for various applications.

II. Background and Related Work

The foundational work by Pierre Alliez et al. provides a comprehensive framework for remeshing techniques that incorporate parameter space mapping and sophisticated sampling strategies. The implementation focuses on adapting these methodologies to facilitate real-time user interaction and mesh customization.

III. System Overview and Contributions

This document elaborates on the architecture of the interactive geometry remeshing system developed in this project. The system is designed to provide a flexible, efficient, and user-driven approach to mesh processing, integrating several computational techniques and user interface innovations to enhance the remeshing process.

A. System Architecture

The architecture of our remeshing system is structured around four core components, each addressing a specific aspect of the mesh processing workflow:

1) **Harmonic Parameterization Module:** This module is responsible for the initial flattening of the 3D mesh into the 2D parameter space. By employing harmonic mappings, we ensure minimal distortion, which is crucial for preserving the intrinsic geometrical properties of the mesh.
2) **Curvature Analysis Module:** After parameterization, this module calculates the curvature at various points of the mesh. The analysis helps in identifying high-curvature regions which are critical for detailed feature preservation in the final mesh.
3) **Control Map Generation:** Leveraging user inputs and the data derived from the curvature analysis, this interactive module allows users to define control maps. Possibility of an integration of control maps as discussed in the paper for the high curavture and area distortion maps.
4) **Sampling and Optimization Module:** This final component of the system utilizes advanced halftoning techniques to sample the mesh according to the specifications set out in the control map. It then performs a series of optimization steps to refine the mesh, improving both its quality and suitability for further processing or visualization.

B. Contributions

- **Enhanced Curvature Analysis:** By advancing the methods used to analyze and interpret mesh curvature, our system allows for more precise identification of areas needing higher detail preservation, thus enabling more intelligent sampling.

- **Real-time Optimization and Feedback:** Our system provides immediate feedback on changes made through the control map, supported by a rapid backend optimization process. This drastically reduces the time needed for users to refine and finalize their meshes.
- **Application Versatility:** The system is designed to be adaptable across various fields requiring high-quality meshes such as computational fluid dynamics, digital content creation, and scientific visualization, proving its utility beyond conventional applications.

These contributions collectively enhance the field of geometric processing, offering substantial improvements in speed, control, and quality of mesh remeshing. Moreover, they pave the way for further research and development in interactive design tools, potentially influencing related disciplines where mesh quality is pivotal.

IV. Geometry Analysis

Geometry analysis forms a critical component of our interactive remeshing system, enabling the identification and enhancement of crucial geometric features within the mesh. This section provides a detailed breakdown of the computational processes and algorithms utilized in the geometry analysis module of the developed system, as demonstrated in the implementation provided in the accompanying Jupyter notebook.

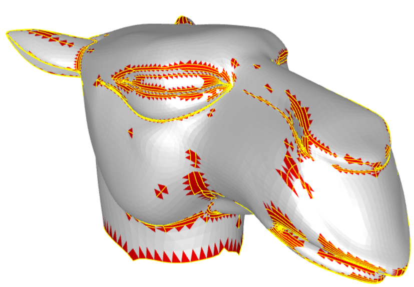

Fig. 1. Creases/ feature lines extracted

A. Harmonic Parameterization

The process begins with the harmonic parameterization of the mesh, which transforms the original 3D mesh into a 2D parameter space while striving to minimize distortion. This is achieved through the solution of a sparse linear system, designed to preserve the local angles of mesh triangles as closely as possible.

- **Boundary Loop Detection:** Initially, the boundary loop of the mesh is identified. This step is crucial as it determines the vertices that lie on the outer edges of the mesh, which will anchor the parameterization process.
- **Circle-to-Square Mapping:** The boundary vertices are then mapped to a circular layout, which is subsequently transformed into a square using a custom circle-to-square mapping function. This function carefully adjusts the positions of the vertices to maintain even spacing and minimize the introduction of stretch into the mesh.

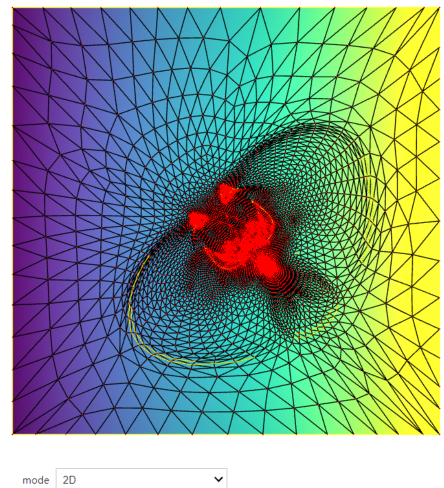

Fig. 2. Creases/ harmonic parameterization

The harmonic parameterization is realized by solving for the interior vertex positions such that the overall energy of the mesh's distortion is minimized. This involves setting up and solving a system of linear equations derived from the mesh's Laplacian and mass matrices.

B. Curvature Analysis

Following parameterization, the curvature of the mesh is analyzed to pinpoint regions of high geometric complexity. This analysis utilizes discrete differential geometry operators to compute curvature at each vertex of the mesh:

- **Gaussian Curvature:** Computed using the angle defect method, where the Gaussian curvature at each vertex is proportional to the angular deficit relative to 2π of the surrounding angles.
- **Principal Curvatures:** Calculated through an eigendecomposition of the shape operator at each vertex, yielding the maximum and minimum curvatures. This step is essential for understanding the mesh's behavior under deformation and stress.

C. Curvature Maps

Utilizing the curvature values computed:

- **Curvature Maps Creation:** Curvature data is normalized and stored in several 2D maps corresponding to Gaussian, mean, maximum, and minimum curvatures. These maps are crucial for the subsequent mesh sampling process,

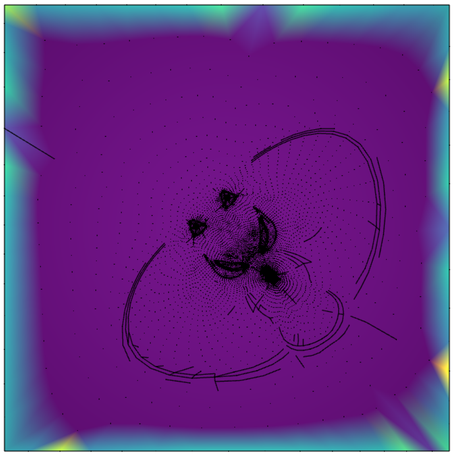

Fig. 3. Detection of areas with high curvature

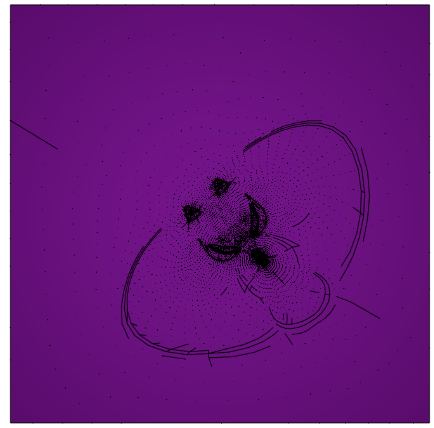

Fig. 4. Area distortion map

informing the system where to allocate more or fewer vertices to capture the mesh's details accurately.
- **Control Map Integration:** The curvature maps are then integrated into a control map. This map combines the localized curvature data with user inputs from the interactive system to dictate vertex density across the mesh during the remeshing process.

D. Mesh Sampling Based on Curvature

With the curvature analyzed and mapped:

- **Mesh Sampling:** The mesh is sampled according to the curvature intensity, with regions of higher curvature receiving a denser distribution of vertices. This selective refinement is critical for preserving sharp features and intricate details in the remeshed output.

E. Optimization and Refinement

Finally, the mesh undergoes an optimization phase where the vertex positions are adjusted to further reduce the distortion introduced during the remeshing process. This optimization is guided by the control map, ensuring that the vertex density aligns with the underlying geometric complexity of the mesh.

- **Vertex Optimization:** Adjustments are made to vertex positions to minimize area distortion and improve aspect ratios, thereby enhancing the visual and functional qualities of the mesh.

This detailed analysis and processing pipeline ensures that the remeshed output not only faithfully represents the original model but also adheres to specified quality and detail requirements, making it suitable for advanced applications in graphics, simulation, and analysis.

V. Mesh Remeshing Techniques

The mesh remeshing techniques utilized in this project are central to achieving high-quality outputs that are tailored to specific requirements such as enhanced feature preservation and optimal sampling density. This section provides a detailed

Fig. 5. Areas of UV faces (a2d) as close as possible to their corresponding 3D face areas (a3d). This is achieved by minimizing the squared difference between these areas.

overview of the methods and algorithms used in our system to achieve efficient and effective remeshing.

A. Control Map Creation

The control map is a pivotal element of our remeshing process. It integrates user inputs with computed data from the geometry analysis phase to guide the remeshing process. The creation of the control map involves several critical steps:

- **Integration of Curvature Data:** Based on the curvature analysis detailed in the previous section, the system generates curvature maps that highlight areas of the mesh with high curvature values. These maps are essential for directing the remeshing process towards areas that require higher vertex densities to preserve detailed geometric features.
- **User Interaction:** The system allows users to interactively modify the control map by specifying regions where they require finer or coarser mesh details. This is facilitated through a graphical user interface that overlays

the curvature maps with interactive tools for adjusting sampling density.

B. Sampling Based on Curvature

Once the control map is established, it guides the sampling process. The objective is to distribute vertices across the mesh in a manner that reflects both the intrinsic geometric properties and user-defined requirements:

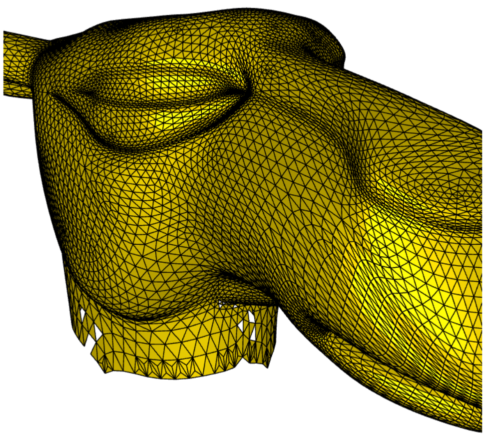

Fig. 6. resampling based on high curvature points by subdividing the mesh

- **Density Adjustment:** Vertex density is adjusted according to the control map, with areas marked for high density receiving more vertices. This step is crucial for capturing complex details in high-curvature regions, such as sharp edges or corners.
- **Sampling Technique:** The system employs an advanced halftoning technique to place vertices according to the specified densities. This method ensures that vertices are distributed in a pattern that maximizes area coverage while adhering to the curvature characteristics of the mesh.

C. Mesh Triangulation and Optimization

After vertices are placed according to the control map, the next steps involve triangulating these vertices and optimizing the resulting mesh:

- **Delaunay Triangulation:** The system performs a Delaunay triangulation on the newly sampled points. This triangulation method is chosen for its mathematical properties that tend to avoid skinny triangles, thereby producing a more uniform mesh surface.
- **Mesh Optimization:** Post-triangulation, the mesh undergoes several optimization procedures aimed at further improving mesh quality. These include edge flipping to improve triangle quality, vertex relocation to reduce distortion, and smoothing techniques to enhance the visual appearance of the mesh.

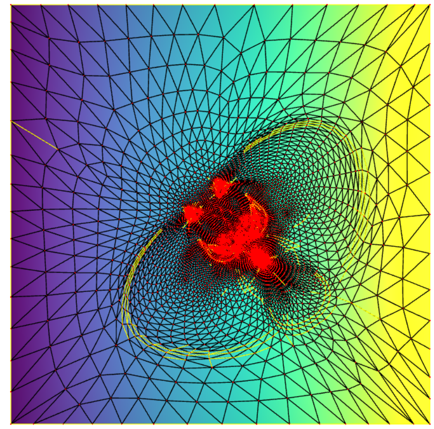

Fig. 7. After applying the delaunay triangulation on the remeshed UV and remeshed F

D. Feature Preservation

An essential aspect of the remeshing process is the preservation of critical features within the mesh:

- **Feature Detection:** Using the curvature maps, the system identifies key features that need to be preserved during remeshing. These features typically include high-curvature edges and vertices that define the character and detail of the model.
- **Feature-Constrained Remeshing:** During the triangulation and optimization phases, these features are treated as constraints. The system ensures that these critical features are not altered during the remeshing process, preserving the integrity and detail of the original model.

This detailed explanation of the mesh remeshing techniques showcases the comprehensive approach taken in this project to enhance mesh quality through intelligent sampling and optimization based on both geometric analysis and user inputs. The resulting system is not only capable of producing high-quality meshes tailored to specific needs but also maintains a high level of interactivity, allowing users to significantly influence the outcome of the remeshing process.

VI. Results

This implementation was successful in integrating a parameterization of a 3d mesh to UV mapping undergoing triangulation for optimized features.

VII. Conclusion and Future Work

A huge part for generating control maps as discussed in the research findings by Pierre et. al. is still yet to demonstrated within this implementation.

References

Pierre Alliez, Mark Meyer, and Mathieu Desbrun. 2002. Interactive geometry remeshing. ACM Transactions on Graphics (TOG) 21, 3 (2002), 347–354.