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The Geometry & Graphics Group at the University of Genova

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Introduction

The Geometry & Graphics Group (G^3) at the University of Genova has been active in the fields of geometric modeling, computer graphics, shape analysis, spatial data structures since 1990. The research of the group focuses on techniques for analyzing, representing, manipulating, generating and visualizing spatial objects. The reference applications are in scientific visualization, data analysis, geographic data processing, computer aided design and animation. Currently, our research follows two major directions: (i) algorithms and data structures for geometric modeling and processing, aimed at increasing efficiency of operations, decreasing memory requirements, and better meeting application needs; (ii) multi-level shape descriptors that are able to disregard geometric details and focus on intrinsic shape properties, depending on user needs (topological methods that capture global features and invariants, and signal processing methods to analyze a shape at different scales).

1. Research in geometric modeling and processing

Our focus is on surfaces and volumes represented through meshes of triangular, quadrilateral, tetrahedral or hexahedral cells.

Data structures for mesh-based shape models. Over the years, we have extensively worked on efficient and effective data structures for meshes, both dimension-specific and dimension-independent, "flat" and hierarchical. Classical data structures, which store adjacencies or incidences to support efficient navigation through a mesh, have high memory requirements for very large meshes or in high dimensions. Our recent alternative solution uses a so-called *stellar decomposition* of the data, implemented through a spatial index, to efficiently reconstruct the local mesh connectivity at run time. This allows saving memory, still with a competitive amortized cost for retrieving connectivity relations [FDW16]. In additional, the generated relations can be targeted to the operations to be performed on the mesh. The framework is dimension-independent and we have used it to extract and simplify morphological features in two, three and higher dimensions [FID*14, IFD16].

Generation of quadrangular and hexahedral meshes. Triangular and tetrahedral meshes are the standard data format produced by reconstruction and meshing methods, but many applications (e.g., CAD, FEM, animation) now prefer or require quadrangular and hexahedral meshes. We started contributing to the generation of quad meshes since 2010, soon being recognized among the leading groups on this subject [BLP*13]. Our most recent contributions are concerned with methods for meshing natural and freeform surfaces with complex geometries and features. We have developed automatic techniques based on either *frame fields* defined on a surface, which produce meshes aligned with surface features, also incorporating anisotropy and skewness [PPT*14, PTP*15, PPM*16], or on *skeletonization*, which produce coarse quad layouts [MTP*15]; and semi-automatic techniques that greatly speed-up retopology tasks in animation, while letting the artist maintain full control on design [ULP*15]. Very recently, we have also extended methods based on skeletonization to generate hexahedral meshes [LMP*16].

Shape segmentation through superpatches. Superpixels and supevoxels have been developed in computer vision to group pixels or voxels into small 2D or 3D regions, thus producing an intermediate representation of the image which allows speeding up image segmentation algorithms. We have developed a similar idea for triangle and tetrahedral meshes discretizing the boundary or the volume of shape, respectively, often endowed with a scalar value [SPD14, PSI*15]. Our method improves over shape segmentation algorithms in terms both of time and memory and is scalable with respect to the mesh size. In particular, it allows to apply the "normalized cut" segmentation on large size tetrahedral meshes. The approach will be extended to quad meshes and to point clouds.

2. Shape analysis and visualization

Unlike geometry, topology deals with qualitative information and permits to filter out relevant information from huge quantities of details. Moreover, topological invariants are robust, coordinate-free, and compact. Thus, topology provides an effective support for classification, retrieval, and visualization [HLH*16].

Discrete Morse complexes for topological shape segmentation We have been working on the segmentation of shapes endowed with a scalar field, with the objective of developing scalable methods for huge size data sets (terrain and volumetric data) [CDM*14]. For this reason, we have designed algorithms based on discrete Morse complexes [CDM*14, DFI*15, CDI*16], devoting our attention to simplification of Morse complexes [FID*14, IFD15] and to topological multi-resolution representations. In [ID14], we have proposed the first combined topological and geometric multi-resolution model: the sequence of simplified representations gener-

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ated by iterating the simplification operator is relaxed into a partial order, described as a directed acyclic graph, and this multi-resolution representation permits to dynamically extract representations of the topology at uniform and variable resolutions.

Efficient homology and persistent homology computation Our research focus is on efficient algorithms and tools for homology and persistent homology computation which would scale well with the size and the dimension of the data, making homological analysis a feasible and desirable tool in practical applications. We have developed a multi-resolution approach to compute homology and homology generators [CDI*14], based on a new minimally complete set of homology- preserving simplification operators, which efficiently supports extracting generators at any desired variable resolution. More recently, we have worked on a tool for homology-preserving simplification of meshes of very large size [IFD16]. We have also approached homology and persistent homology computation based on the construction of a discrete Morse complex having the same homological properties as the input shape. We have developed the first efficient algorithm for computing the discrete Morse gradient and complex on "triangle" meshes in arbitrary dimensions [FID14], as well as a compact implicit representation of the discrete Morse gradient. Our very recent fork focus on applying discrete Morse theory to the analysis of data endowed with multiple scalar functions for multipersistent homology computation [SIL*16].

Multi-scale shape analysis. By adopting a signal processing approach, we treat geometric and time-varying data (surfaces and trajectories) as domains of scalar fields. We study the evolution of critical points of such fields across progressively simplified levels of input data, obtained through either a filtering process acting in the frequency domain, or a topological simplification process acting in the amplitude domain, or both. Our approach constructs a virtually continuous scale-space that allows us to rank the importance of critical points and to select the best scale at which they correspond to representative features. We have applied our method to terrain data [RJP16] and to the identification of fiducial points for face recognition in 3D [DRP15]. Most recently, we are applying the same techniques to the segmentation of time sequences from motion capture and to the qualitative analysis of movement.

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