INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team Geometrica

Geometric Computing

Sophia Antipolis - Méditerranée - Futurs

THEME SYM

Activity Report

2007

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2. Overall Objectives

2.1. Introduction

Geometric computing plays a central role in most engineering activities: geometric modelling, computer aided design and manufacturing, computer graphics and virtual reality, scientific visualization, geographic information systems, molecular biology, fluid mechanics, and robotics are just a few well-known examples. The rapid advances in visualization systems, networking facilities and 3D sensing and imaging make geometric computing both dominant and more demanding concerning effective algorithmic solutions.

Computational geometry emerged as a discipline in the seventies and has met with considerable success in resolving the asymptotic complexity of basic geometric problems including data structures, convex hulls, triangulations, Voronoi diagrams, geometric arrangements and geometric optimization. However, in the mid-nineties, it was recognized that the applicability in practice of computational geometry techniques was far from satisfactory and a vigorous effort has been undertaken to make computational geometry more effective. The PRISME project together with several partners in Europe took a prominent role in this research and in the development of a large library of computational geometry algorithms, CGAL.

GEOMETRICA aims at pursuing further the effort in this direction and at building upon the initial success. Its focus is on effective computational geometry with special emphasis on *curves and surfaces*. This is a challenging research area with a huge number of potential applications in almost all application domains involving geometric computing.

The overall objective of the project is to give effective computational geometry for curves and surfaces solid mathematical and algorithmic foundations, to provide solutions to key problems and to validate our theoretical advances through extensive experimental research and the development of software packages that could serve as steps toward a standard for safe and effective geometric computing.

2.2. Highlights of the year

Year 2007 has seen the creation of the project-team ABS. ABS is lead by Frédéric Cazals (DR INRIA) and includes Julie Bernauer (CR INRIA, since December 1st), Benjamin Bouvier (PostDoc, INRIA) and Sebastien Loriot (Phd Student). Frédéric Cazals, Benjamin Bouvier and Sebastien Loriot were previuosly members of GEOMETRICA. The project-team ABS aims at carrying on research at the interface of Computer Science and Structural Biology. Because the project-team ABS has its own acitvity report and although the creation of ABS occured only on July 1st, we have decided to remove from the activity report of GEOMETRICA all items related to the activity of the the ABS members Frédéric Cazals, Benjamin Bouvier and Sebastien Loriot.

Pierre Alliez and David Cohen-Steiner won the best paper award at the fifth EUROGRAPHICS Symposium on Geometry Processing, July 2007.

Pierre Alliez and Christian Rössl won the SIGGRAPH NVIDIA award for the best course notes in August 2007.

Monique Teillaud defended her «Habilitation à diriger des recherches» entitled '– Computational geometry – From theory to practice, From linear objects to curved objects", on September 25.

3. Scientific Foundations

3.1. Introduction

The research conducted by GEOMETRICA focuses on three main directions:
- fundamental geometric data structures and algorithms
- robust computation and advanced programming,
- shape approximation and mesh generation.

3.2. Fundamental geometric data structures and algorithms

GEOMETRICA is pursuing long standing research on fundamental geometric data structures and algorithms. GEOMETRICA has a large expertise in Voronoi diagrams and Delaunay triangulations, randomized algorithms, combinatorial geometry and related fields. Recently, we devoted efforts to developing the field of computational geometry beyond linear objects. We are especially interested in developing a theory of curved Voronoi diagrams. Such diagrams allow researchers to model growing processes and have important applications in biology, ecology, chemistry and other fields. They also play a role in some optimization problems and in anisotropic mesh generation. Euclidean Voronoi diagrams of non punctual objects are also non affine diagrams. They are of particular interest to robotics, CAD and molecular biology. Even for the simplest diagrams, e.g. Euclidean Voronoi diagrams of lines, triangles or spheres in 3-space, obtaining tight combinatorial bounds and efficient algorithms are difficult research questions. In addition, effective implementations require us to address specific algebraic and arithmetic questions. Carefully working out the robustness issues is a central objective of GEOMETRICA (see below).
In the past years, the main objective of computational geometry has been the design of time efficient algorithms, either from the theoretical point of view of the asymptotic complexity or the more practical aspect of running efficient benchmarks. Surprisingly, less interest has been devoted to improve the space behavior of such algorithms although the problem may become important when the main memory is insufficient and the system has to swap to find extra memory space; this may happen either for massive data or for small memory devices such as PDA. GEOMETRICA intends to attack this problem from several aspects:
— the compression of geometrical objects for storage or network transmission purposes
— the design of algorithms accessing locally the memory to reduce (but not remove) the swapping in memory
— the design of new data-structures to represent geometrical objects using less memory.
For all these aspects we are interested in both the theoretical asymptotic sizes involved and the practical aspect for reasonable input size. Such a distinction between asymptotic behavior and practical interest may appear strange since we are interested in massive data, but even for a very big mesh of several million points which can be called “massive data”, we are still far from the asymptotic behavior of some theoretical structures.

3.3. Robust computation and advanced programming

An implementation of a geometric algorithm is called *robust* if it produces a valid output for all inputs. Geometric programs are notorious for their non-robustness due to two reasons: (1) geometric algorithms are designed for a model of computation where real numbers are dealt with exactly and, (2) geometric algorithms are frequently only formulated for inputs in general position. As a result, implementations may crash or produce nonsensical outputs.

The importance of robustness in geometric computations has been recognized for a long time, but significant progress was made only in recent years. GEOMETRICA held a central role in this process, including advances regarding the *exact computation paradigm*. In this paradigm, robustness is achieved by a combination of three methods: *exact arithmetic*, *dedicated arithmetic* (such as interval arithmetic and other kinds of arithmetic filters) and *controlled rounding*. Techniques such as *symbolic perturbations* are also used to handle degenerate inputs.

In addition to pursuing research on robust geometric computation, GEOMETRICA is an active member of the Open Source Project developing a large library named CGAL. This library makes extensive use of generic programming techniques and is both a unique tool to perform experimental research in Computational Geometry and a comprehensive library for Geometric Computing. The company GEOMETRY FACTORY was started in 2003 to commercialize components from CGAL and to offer services for geometric applications. See Section 5.1 for more details.

3.4. Shape approximation and mesh generation

Complex shapes are ubiquitous in robotics (configuration spaces), computer graphics (animation models) or physical simulations (fluid models, molecular systems). In all these cases, no natural *shape space* is available or when such spaces exist they are not easily dealt with. When it comes to performing calculations, the objects under study must be discretized. On the other hand, several application areas such as Computer Aided Geometric Design or medical imaging require reconstructing $3D$ or $4D$ shapes from samples.

The aforementioned questions fall in the realm of *geometric approximation theory*, a topic GEOMETRICA is actively involved in. More precisely, the generation of samples, the definition of differential quantities (e.g. curvatures) in a discrete setting, the geometric and topological control of approximations, as well as multi-scale representations are investigated. Connected topics of interest are also the progressive transmission of models over networks and their compression.

Surface mesh generation and surface reconstruction have received a great deal of attention by researchers in various areas ranging from computer graphics through numerical analysis to computational geometry. However, work in these areas has been mostly heuristic and the first theoretical foundations have been established only recently. Quality mesh generation amounts to finding a partition of a domain into linear elements (mostly triangles or quadrilaterals) with topological and geometric properties. Typically, one aims at constructing a piecewise linear (PL) approximation with the "same" topology as the original surface (same topology may have several meanings). In some contexts, one wants to simplify the topology in a controlled manner. Regarding the geometric distance between the surface and its PL approximation, different measures must be considered: Hausdorff distance, errors on normals, curvatures, areas etc. In addition, the shape, angles or size of the elements must match certain criteria. We call *remeshing* the techniques involved when the input domain to be discretized is itself discrete. The input mesh is often highly irregular and non-uniform, since it typically comes as the output of a surface reconstruction algorithm applied to a point cloud obtained from a scanning device. Many geometry processing algorithms (e.g. smoothing, compression) benefit from remeshing, combined with uniform or curvature-adapted sampling. GEOMETRICA intends to contribute to all aspects of this matter, both in theory and in practice.

Volumetric mesh generation consists in triangulating a given three-dimensional domain with tetrahedra having a prescribed size and shape. For instance, the tetrahedra in a general purpose mesh should be as regular as possible (isotropic case), whereas they should be elongated in certain directions for problem specific meshes. Volumetric mesh generation often makes use of surface mesh generation techniques (*e.g.* to approximate the boundary of the domain or interfaces between two media). Thanks to its strong experience with Delaunay triangulations, GEOMETRICA recently made several contributions to the generation of volumetric meshes, and intends to pursue in this direction.

4. Application Domains

4.1. Geometric modeling and shape reconstruction

Keywords: *Geometric modeling*, *geology*, *medical imaging*, *reverse engineering*, *surface reconstruction*.

Modeling 3D shapes is required for all visualization applications where interactivity is a key feature since the observer can change the viewpoint and get an immediate feedback. This interactivity enhances the descriptive power of the medium significantly. For example, visualization of complex molecules helps drug designers to understand their structure. Multimedia applications also involve interactive visualization and include e-commerce (companies can present their product realistically), 3D games, animation and special effects in motion pictures. The uses of geometric modeling also cover the spectrum of engineering, computer-aided design and manufacture applications (CAD/CAM). More and more stages of the industrial development and production pipeline are now performed by simulation, due to the increased performance of numerical simulation packages. Geometric modeling therefore plays an increasingly important role in this area. Another emerging application of geometric modeling with high impact is medical visualization and simulation.

In a broad sense, shape reconstruction consists of creating digital models of real objects from points. Example application areas where such a process is involved are Computer Aided Geometric Design (making a car model from a clay mockup), medical imaging (reconstructing an organ from medical data), geology (modeling underground strata from seismic data), or cultural heritage projects (making models of ancient and or fragile models or places). The availability of accurate and fast scanning devices has also made the reproduction of real objects more effective such that additional fields of applications are coming into reach. The members of GEOMETRICA have a long experience in shape reconstruction and contributed several original methods based upon the Delaunay and Voronoi diagrams.

4.2. Scientific computing

Keywords: *Unstructured meshes*, *finite element method*, *finite volume method*.

Meshes are the basic tools for scientific computing using finite element methods. Unstructured meshes are used to discretize domains bounded by complex shapes while allowing local refinements. GEOMETRICA contributes to 2D, 3D as well as surface mesh generation. Most of our methods are based upon Delaunay triangulations, Voronoi diagrams and their variants. Affine diagrams are used in the context of volume element methods, while non-affine diagrams are used to generate anisotropic meshes. We investigate in parallel both greedy and variational mesh generation techniques. The greedy algorithms consist of inserting vertices in an initial coarse mesh using the Delaunay refinement paradigm, while the variational algorithms consists of minimizing an energy related to the shape and to the size of the elements. Our goal is to show the complementarity of these two paradigms. Quadrangle surface meshes are also of interest for reverse engineering and geometry processing applications. Our approach consists of sampling a set of curves on the surface so as to control the final edge alignment, the mesh sizing and the regularity of the quadrangulation.

4.3. Algorithmic issues in Structural Biology

Applications related to issues in structural biology are now described in the activity report of the ABS project-team.

5. Software

5.1. CGAL, the Computational Geometry Algorithms Library

Participants: Pierre Alliez, Jean-Daniel Boissonnat, Manuel Caroli, Christophe Delage, Olivier Devillers, Pedro Machado Manhães de Castro, Abdelkrim Mebarki, Naceur Meskini, Andreas Meyer, Sylvain Pion [contact person], Laurent Rineau, Laurent Saboret, Monique Teillaud, Camille Wormser, Mariette Yvinec.

With the collaboration of Hervé Brönnimann, Frédéric Cazals, Frank Da, Andreas Fabri, Julia Flötotto, Philippe Guigue, Menelaos Karavelas, Sébastien Loriot, Marc Pouget,François Rebufat, Radu Ursu.

http://www.cgal.org

CGAL is a C++ library of geometric algorithms initially developed within two European projects (project ESPRIT IV LTR CGAL December 97 - June 98, project ESPRIT IV LTR GALIA November 99 - August 00) by a consortium of eight research teams from the following institutes: Universiteit Utrecht, Max-Planck Institut Saarbrücken, INRIA Sophia Antipolis, ETH Zürich, Tel Aviv University, Freie Universität Berlin, Universität Halle, RISC Linz. CGAL became an Open Source Project in November 2003.

The goal of CGAL is to make the solutions offered by the computational geometry community available to the industrial world and applied domains.

The CGAL library consists of a kernel, a list of algorithmic packages, and a support library. The kernel is made of classes that represent elementary geometric objects (points, vectors, lines, segments, planes, simplices, isothetic boxes, circles, spheres, circular arcs...), as well as affine transformations and a number of predicates and geometric constructions over these objects. These classes exist in dimensions 2 and 3 (static dimension) and d (dynamic dimension). Using the template mechanism, each class can be instantiated following several representation modes : we can choose between Cartesian or homogeneous coordinates, use different types to store the coordinates, and use reference counting or not. The kernel also provides some robustness features using some specifically-devised arithmetic (interval arithmetic, multi-precision arithmetic, static filters...).

A number of packages provide geometric data structures as well as algorithms. The data structures are polygons, polyhedra, triangulations, planar maps, arrangements and various search structures (segment trees, d-dimensional trees...). Algorithms are provided to compute convex hulls, Voronoi diagrams, boolean operations on polygons, solve certain optimization problems (linear, quadratic, generalized of linear type). Through class and function templates, these algorithms can be used either with the kernel objects or with user-defined geometric classes provided they match a documented interface (concept).

Finally, the support library provides random generators, and interfacing code with other libraries, tools, or file formats (ASCII files, QT or LEDA Windows, OpenGL, Open Inventor, Postscript, Geomview, ...). Partial interfaces with Python, SCILAB and the Ipe drawing editor are also now available.

GEOMETRICA is particularly involved in general maintainance, in the arithmetic issues that arise in the treatment of robustness issues, in the kernel, in triangulation packages and their close applications such as alpha shapes, in meshes... Three researchers of GEOMETRICA are members of the CGAL Editorial Board, whose main responsibilities are the control of the quality of CGAL, making decisions about technical matters, coordinating communication and promotion of CGAL.

CGAL is about 600,000 lines of code and supports various platforms: GCC (Linux, Mac OS X, Solaris, Cygwin...), Visual C++ (Windows), Intel C++... Version 3.3 has been released in June 2007, with a subsequent bug-fix release 3.3.1 in September. The previous main release, CGAL 3.2, has been downloaded 15000 times from our web site, during the 13 months period where it was the main version. Moreover, CGAL is now directly available as packages for the Debian, Ubuntu and Fedora Linux distributions.

More numbers about CGAL: there are now 12 editors in the editorial board, with approximately 30 additional developers. The user discussion mailing-list has more than 900 subscribers with a relatively high traffic of 5 mails a day on average. The announcement mailing-list has almost 3000 subscribers.

CGAL is distributed under an Open Source license (LGPL or QPL depending on which packages), and is commercialized by GEOMETRY FACTORY, a company *Born of INRIA*, founded in 2003 by Andreas Fabri.

5.2. Web service

5.2.1. A web service for surface reconstruction

Participant: David Cohen-Steiner.

In collaboration with Frank Da and Andreas Fabri. http://cgal.inria.fr/Reconstruction/.

The surface reconstruction algorithm developed by D. Cohen-Steiner and F. Da using CGAL is available as a *web service*. Via the web, the user uploads the point cloud data set to the server and obtains a VRML file of the reconstructed surface, which gets visualized in the browser of the user. This allows the user to check if the algorithm fits his/her needs, to learn how to adjust the parameters, before contacting INRIA to obtain an executable. It also provides us with the opportunity to collect real-world data sets used for testing and improving our reconstruction algorithms.

6. New Results

6.1. Introduction

The presentation of our new results follows the three main directions listed in Section 3.1

– fundamental geometric data structures and algorithms,
– robust computation and advanced programming,
– shape approximation and mesh generation.

6.2. Combinatorics, data structures and algorithms

Keywords: *Triangulations*, *Voronoi diagrams*, *compact data structures*, *periodic spaces*, *projective geometry*.

6.2.1. Umbra and penumbra computation

Participant: Olivier Devillers.

In collaboration with J. Demouth, H. Everett, M. Glisse S. Lazard (INRIA-Vegas) and R. Seidel (Saarland University)

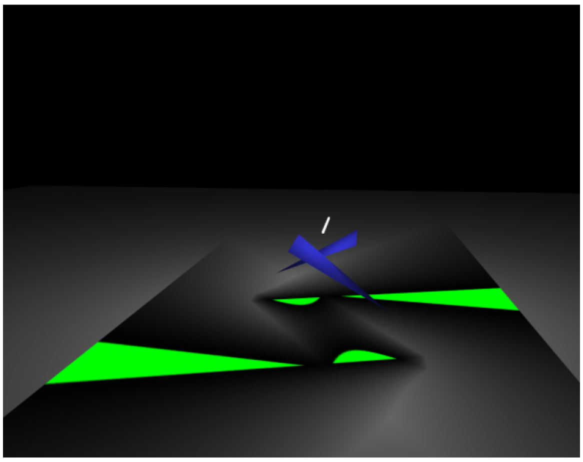

Figure 1. Two triangles and a segment light sources with an umbra region (in green) with 4 connected components

Computing shadow boundaries is a difficult problem in the case of non-point light sources. We say that a point is in the umbra if it does not see any part of any light source; it is in full light if it sees entirely all the light sources; otherwise, it is in the penumbra. While the common boundary of the penumbra and the full light is well-understood, less is known about the boundary of the umbra. In this paper we prove various bounds on the complexity of the umbra cast by a segment light source on a plane in the presence of polygon or polytope obstacles. In particular, we show that a single segment light source may cast, in the presence of two triangles, four connected components of umbra (see Figure 1) and that two fat convex obstacles of total complexity n can have $\Omega(n)$ connected components of umbra. In a scene consisting of a segment light source and k disjoint polytopes of total complexity n, we prove an $\Omega(nk^2 + k^4)$ lower bound on the maximum number of connected components of the umbra and a $O(nk^3)$ upper bound on its complexity. These are the first bounds on the size of the umbra in terms of both k and n. These results prove that the umbra, which is bounded by arcs of conics, is intrinsically much more intricate than the full light/penumbra boundary which has complexity $O(n\alpha(k) + k^2)$ and is bounded by line segments [39], [56].

6.2.2. Random sampling of a cylinder yields a not so nasty Delaunay triangulation

Participant: Olivier Devillers.

In collaboration with J. Erickson (University of Illinois at Urbana Champaign) and X. Goaoc (INRIA-Vegas)

We prove that the expected size of the 3D Delaunay triangulation of n points evenly distributed on a cylinder is $\Theta(n \log n)$. This shows that the $n\sqrt{n}$ behavior of the cylinder-example of Erickson is pathological [58].

6.2.3. Helly-type theorems for approximate covering

Participant: Olivier Devillers.

In collaboration with J. Demouth, M. Glisse and X. Goaoc (INRIA-Vegas)

In some cases, if a family $\mathcal{F}$ of sets of a certain kind covers some particular set Ω, then sub-family of $\mathcal{F}$ of size k covering Ω can be found (for some k). An easy example is given by $\mathcal{F}$ a family of length 1 intervals in $I\!R$, Ω any point and $k = 2$.

In this work, we investigate approximate versions of such theorems. We prove that if a sphere Ω is covered by a family $\mathcal{F}$ of spheres, then we can extract a finite sub-family that almost cover Ω. If ϵ is the non covered volume of Ω, then the size of the family is $O(\epsilon^{\frac{1-d}{2}} \text{polylog} \frac{1}{\epsilon})$. We then extend these results in several directions, including covering boxes by boxes and visibility among disjoint unit balls in $I\!R^3$ [57]

6.2.4. Triangulations in the projective plane

Participants: Mridul Aanjaneya, Monique Teillaud.

We consider the problem of computing a triangulation of the real projective plane $\mathbb{P}^2$, given a finite point set $\mathcal{P} = \{p_1, p_2, ..., p_n\}$ as input [50], [27]. We prove that a triangulation of $\mathbb{P}^2$ always exists if at least six points in $\mathcal{P}$ are in *general position*, i.e., no three of them are collinear. We also design a worst-case time $\mathcal{O}(n^2)$ (in the RAM model) algorithm for triangulating $\mathbb{P}^2$ if this necessary condition holds. As far as we know, this is the first computational result on the real projective plane.

6.2.5. Triangulations in the 3D torus

Participants: Manuel Caroli, Monique Teillaud.

This work was started during the short post-doctoral stay of Nico Kruithof in GEOMETRICA *in 2006.*

CGAL currently provides packages to compute triangulations in $\mathbb{R}^2$ and $\mathbb{R}^3$. Periodic spaces are widely used in application areas like simulations. We started to work on algorithms to compute triangulations in the periodic space $[0,1]^3$, which is a representation of the 3D hypersurface of a torus in 4D.

We proposed a new design for the 3D triangulation package that permits to easily add functionality to compute triangulations in other spaces. These design changes have been implemented, and validated on the case of the periodic space $\mathbb{T}^3$ [52]. They will be integrated in further CGAL releases.

6.2.6. Bregman Voronoi Diagrams: Properties, Algorithms and Applications

Participant: Jean-Daniel Boissonnat.

In collaboration with Frank Nielsen (Sony CSL) and Richard Nock (CEREGMIA)

We have pursued and extended our work on Bregman Voronoi diagrams. A full version of the paper is now available [59]. New results include results on Bregman balls (e.g. their VC-dimension is finite), extensions of these diagrams to k-order and k-bag Bregman Voronoi diagrams, the study of Bregman triangulations and their connexion with Bregman Voronoi diagrams. We show that these triangulations capture many of the properties of the celebrated Delaunay triangulation. Finally, we give some applications of Bregman Voronoi diagrams which are of interest in the context of computational geometry, machine learning, vector quantification and clustering.

6.2.7. A disk-covering problem with application in optical interferometry

Participants: Jean-Daniel Boissonnat, Trung Nguyen.

In collaboration with Frédéric Falzon (Thalès Alenia Space) a Christian Knauer (Freie Universität, Berlin).

Given a disk O in the plane called the objective, we want to find n small disks $P_1, ..., P_n$ called the pupils such that $\cup_{i,j=1}^{n} Pi \ominus Pj \supset O$, where $\ominus$ denotes the Minkowski difference operator, while minimizing the number of pupils, the sum of the radii or the total area of the pupils. This problem is motivated by the construction of very large telescopes from several smaller ones by so-called Optical Aperture Synthesis. In [40], we provide exact, approximate and heuristic solutions to several variations of the problem.

6.3. Geometric computing

Keywords: *curves*, *predicates*, *robustness*, *surfaces*.

6.3.1. Circles and circular arcs in 2D

Participants: Pedro Machado Manhães de Castro, Sylvain Pion, Monique Teillaud.

Most of this work was done while Pedro Machado Manhães de Castro was visiting GEOMETRICA *in 2006, in the framework of the INRIA Intership Programme.*

The first version of a kernel for circles and circular arcs in 2D was released in CGAL 3.2. We studied a variety of techniques that we tested to improve the efficiency of this 2D circular kernel [62], [49]. These improvements are motivated by applications to VLSI design, and real VLSI industrial data are used to measure the impact of the techniques used to enhance this kernel (Figure 2). The improvements were integrated in CGAL.

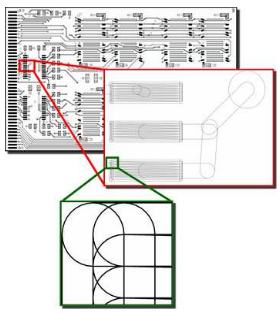

Figure 2. CGAL *experiments with* VLSI *data (courtesy of* MANIA BARCO *and* GEOMETRY FACTORY*).*

6.3.2. Spheres, circles and circular arcs in 3D

Participants: Pedro Machado Manhães de Castro, Monique Teillaud.

In collaboration with Frédéric Cazals and Sébastien Loriot (ABS project-team).

The first part of this work was partially done while Pedro Machado Manhães de Castro was visiting GEOMETRICA *in 2006, in the framework of the INRIA Intership Programme.*

A 3D kernel for the manipulations of spheres, circles and circular arcs in 3D was submitted to the CGAL Editorial board. The package follows the same overall design as the 2D circular kernel. It proposes functionalities involving these objects. It also defines the concept of an algebraic kernel dedicated to the special case of spheres, lines and circles in 3D [61].

More recently, we proposed a way to expand this package by adding objects and functionalities dedicated to the case where all the objects handled are located on a reference sphere. We showed how the two frameworks can be combined [65].

6.3.3. Algebraic Kernel

Participant: Monique Teillaud.

This work is a collaboration with Eric Berberich, MPI Saarbrücken, Michael Hemmer, University of Mainz, and Menelaos Karavelas, University of Crete.

We revised the specification of the algebraic kernel concept for CGAL [51]. These specifications concern the algebraic kernel for polynomials in one and two variables. They are currently under review by the CGAL Editorial Board.

6.4. Geometric approximation

Keywords: *Computational topology*, *geometric inference*, *geometric probing*, *implicit surfaces*, *point set surfaces*, *surface learning*, *surface meshing*.

6.4.1. Voronoi-based Variational Reconstruction of Unoriented Point Sets

Participants: Pierre Alliez, David Cohen-Steiner.

Work in collaboration with Yiying Tong and Mathieu Desbrun from Caltech.

We introduce an algorithm for reconstructing watertight surfaces from unoriented point sets [29]. Using the Voronoi diagram of the input point set, we deduce a tensor field whose principal axes and eccentricities locally represent respectively the most likely direction of the normal to the surface, and the confidence in this direction estimation. An implicit function is then computed by solving a generalized eigenvalue problem such that its gradient is most aligned with the principal axes of the tensor field, providing a best-fitting isosurface reconstruction. The implicit function optimization provides resilience to noise, adjustable fitting to the data, and controllable smoothness of the reconstructed surface. Finally, the use of simplicial meshes and anisotropic Laplace operators renders the numerical treatment simple and robust.

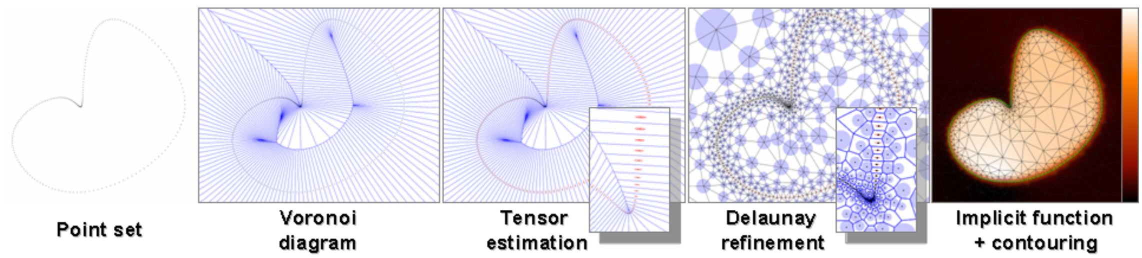

Figure 3. Voronoi-based shape reconstruction illustrated in 2D (also applies to 3D).

6.4.2. Shape reconstruction from unorganized cross-sections

Participants: Jean-Daniel Boissonnat, Pooran Memari.

We consider the problem of reconstructing a shape from unorganized cross-sections [35]. The main motivation for this problem comes from medical imaging applications where cross-sections of human organs are obtained by means of a free hand ultrasound apparatus. The position and orientation of the cutting planes may be freely chosen which makes the problem substantially more difficult than in the case of parallel cross-sections, for which a rich literature exists. The input data consist of the cutting planes and (an approximation of) their intersection with the object. Our approach consists of two main steps. First, we compute the arrangement of the cutting planes. Then, in each cell of the arrangement, we reconstruct an approximation of the object from its intersection with the boundary of the cell. Lastly, we glue the various pieces together. The method makes use of the Delaunay triangulation and generalizes the reconstruction method of Boissonnat and Geiger for the case of parallel planes. The analysis provides a neat characterization of the topological properties of the result and, in particular, shows an interesting application of Moebius diagrams to compute the locus of the branching points. We have im plemented our algorithm in C++, using the CGAL library. Experimental results show that the algorithm performs well and can handle complicated branching configurations.

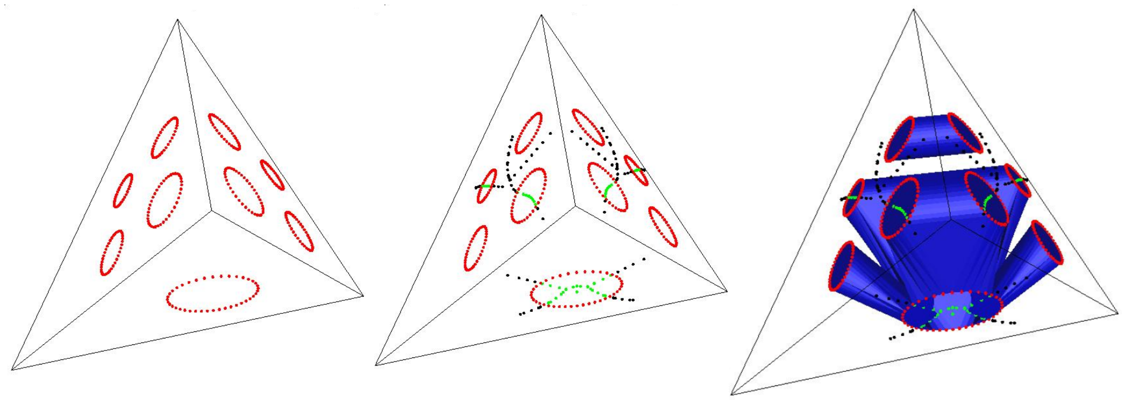

Figure 4. Reconstruction with multiple branching between the sections: (left) Input. (middle) Input points in red and the added branching points in green. (right) Reconstructed object.

6.4.3. Manifold Reconstruction in Arbitrary Dimensions using Witness Complexes

Participant: Jean-Daniel Boissonnat.

Work in collaboration with Leo Guibas and Steve Oudot from Stanford university.

It is a well-established fact that the witness complex is closely related to the restricted Delaunay triangulation in low dimensions. Specifically, it has been proved that the witness complex coincides with the restricted Delaunay triangulation on curves, and is still a subset of it on surfaces, under mild sampling assumptions. Unfortunately, these results do not extend to higher-dimensional manifolds, even under stronger sampling assumptions. In [34], we show how the sets of witnesses and landmarks can be enriched, so that the nice relations that exist between both complexes still hold on higher-dimensional manifolds. We also use our structural results to devise an algorithm that reconstructs manifolds of any arbitrary dimension or co-dimension at different scales. The algorithm combines a farthest-point refinement scheme with a vertex pumping strategy. It is very simple conceptually, and it does not require the input point sample W to be sparse. Its time complexity is bounded by $c(n)|W|^2$, where $c(n)$ is a constant depending solely on the dimension n of the ambient space.

6.4.4. Shape Smoothing using Double Offsets

Participants: Frédéric Chazal, David Cohen-Steiner.

This work is a collaboration with André Lieutier (Dassault Systèmes) and Boris Thibert (Grenoble).

It has been observed for a long time that offsetting a solid by a radius r and then offsetting the complement by a radius $d < r$ produces, in some cases, a new solid with the same topology but with a smooth boundary (see figure 5). While this fact has been widely used in Computer Aided Geometric design or in the field of image processing, we provide in this work [38] for the first time a tight and robust condition that guarantees the smoothness of the new solid and gives a lower bound on the reach (distance to the medial axis). This condition is based on general properties of distance functions and relies on the recently introduced critical function and μ-reach.

6.4.5. Inferring Local Homology from Sampled Stratified Spaces

Participant: David Cohen-Steiner.

This work is a collaboration with Paul Bendich, Herbert Edelsbrunner, John Harer, and Dmitriy Morozov from Duke University.

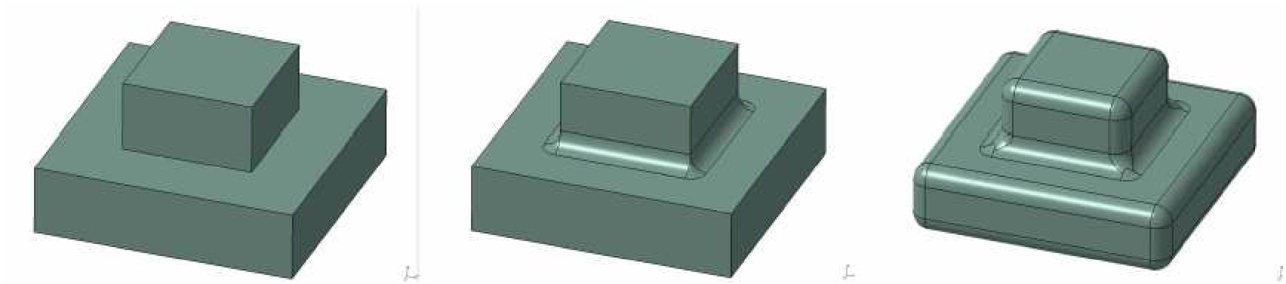

Figure 5. Double offset operation.

We study the reconstruction of a stratified space from a possibly noisy point sample [33]. Our approach relies on vineyards, which are the curves traced by the persistence diagrams of continuous 1-parameter families of functions. Specifically, we use the vineyard of the distance function restricted to 1-parameter family of neighborhoods of a point to assess the local homology of the stratified space at that point. We prove the correctness of this assessment under the assumption of a sufficiently dense sample. We also give an algorithm that constructs the vineyard and makes the local assessment in time at most cubic in the size of the Delaunay triangulation of the point sample.

6.4.6. Stability of Boundary Measures

Participants: Frédéric Chazal, David Cohen-Steiner, Quentin Mérigot.

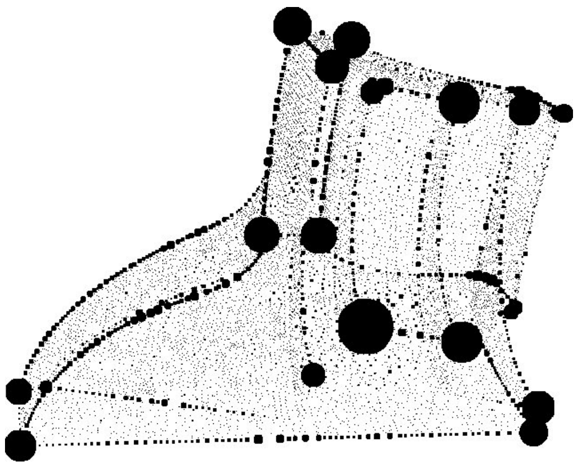

Figure 6. Boundary measure of a mechanical part. The size of the disks indicates the local intensity of the measure.

We introduce the *boundary measure* at scale r of a compact subset K of Euclidean space. It is the mass distribution on K such that the mass of a region is the volume of the r-offset of K that projects in the region. We show how it can be computed efficiently for point clouds and suggest these measures can be used for feature detection (see figure 6). The main contribution of this work [55] is the proof of a quantitative stability theorem for boundary measures using tools from convex analysis and geometric measure theory. As a corollary we obtain a stability result for Federer's curvature measures of a compact set, which shows that they can be computed from point cloud approximations.

6.4.7. Normal Cone Approximation and Offset Shape Isotopy

Participants: Frédéric Chazal, David Cohen-Steiner.

This work is a collaboration with André Lieutier (Dassault Systèmes).

This work [54] addresses the problem of approximating the normals to general compact sets in Euclidean space. It is proven that under certain sampling conditions, it is possible to approximate the gradient vector field of the distance function to general compact sets. These conditions involve the μ-reach of the compact set, a recently introduced notion of feature size. As a consequence, we provide a sampling condition that is sufficient to ensure the correctness up to isotopy of the reconstruction given by an offset of the sampling. we also provide a notion of normal cone that is stable under perturbations.

6.5. Mesh generation

Keywords: *Isotropic meshing*, *anisotropic meshing*, *level sets*, *mesh sizing*, *optimized meshing*, *tetrahedral meshing*, *triangle meshing*.

6.5.1. Meshing 3D domains bounded by piecewise smooth surfaces

Participants: Laurent Rineau, Mariette Yvinec.

We propose [45] an algorithm to mesh 3D domains bounded by piecewise smooth surfaces (see Figure 7). The algorithm may handle multivolume domains defined by non connected or non manifold surfaces. The boundary and subdivision surfaces are assumed to be described by a complex formed by surface patches stitched together along curve segments.

The meshing algorithm is a Delaunay refinement. It uses the notion of restricted Delaunay triangulation to approximate the input curve segments and surface patches. The algorithm yields a mesh with good quality tetrahedra and offers a user control on the size of the tetrahedra. The vertices in the final mesh have a restricted Delaunay triangulation to any input feature which is a homeomorphic and accurate approximation of this feature. The algorithm also provides guarantee on the size and shape of the facets approximating the input surface patches. In its current state the algorithm suffers from a severe angular restriction on input constraints. It basically assumes that two linear subspaces that are tangent to non incident and non disjoint input features on a common point form an angle measuring at least 90 degrees.

6.5.2. High-quality consistent meshing of multi-label datasets

Participants: Jean-Daniel Boissonnat, Laurent Rineau, Mariette Yvinec.

In collaboration with Jean-Philippe Pons, Florent Ségonne and Renaud Keriven from CERTIS, École Nationale des Ponts et Chaussées.

In [44], we extend some recent provably correct Delaunay-based meshing algorithms to the case of multi-label partitions, so that they can be applied to the generation of high-quality geometric models from labeled med- ical datasets. Our approach enforces watertight surface meshes free of self- intersections, and outputs surface and volume meshes of the different tissues which are consistent with each other, including at multiple junctions. The algorithm relies on an oracle that given a point in space, answers which tissue it belongs to. This abstraction of the tissue partition makes our approach applicable to virtually any combination of data sources. Finally, our approach offers extensive control over the size and shape of mesh elements, through customizable quality criteria on triangular facets and on tetrahedra, which can be tuned independently for the different anatomical structures. Our numerical experiments demonstrate the effectiveness and flexibility of our approach for generating high-quality surface and volume meshes from real multi-label medical datasets. See Figure 8.

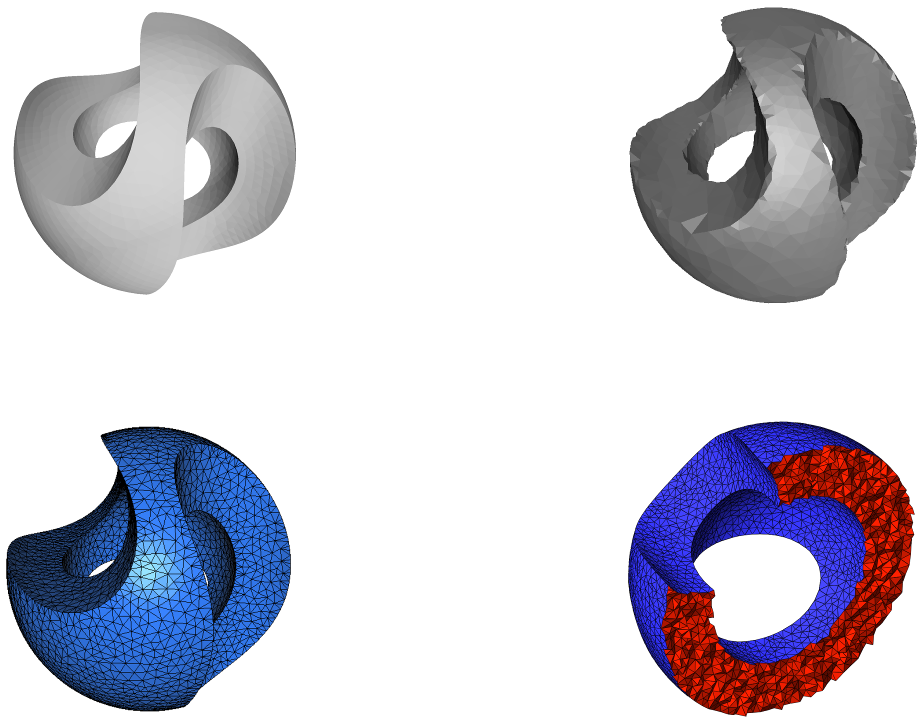

Figure 7.

Meshing domains bounded by piecewise smooth surfaces.
***upleft**: the input surface, **upright**: a mesh that does not respect sharp edges*
***downleft and downright**: a mesh respecting sharp edges*

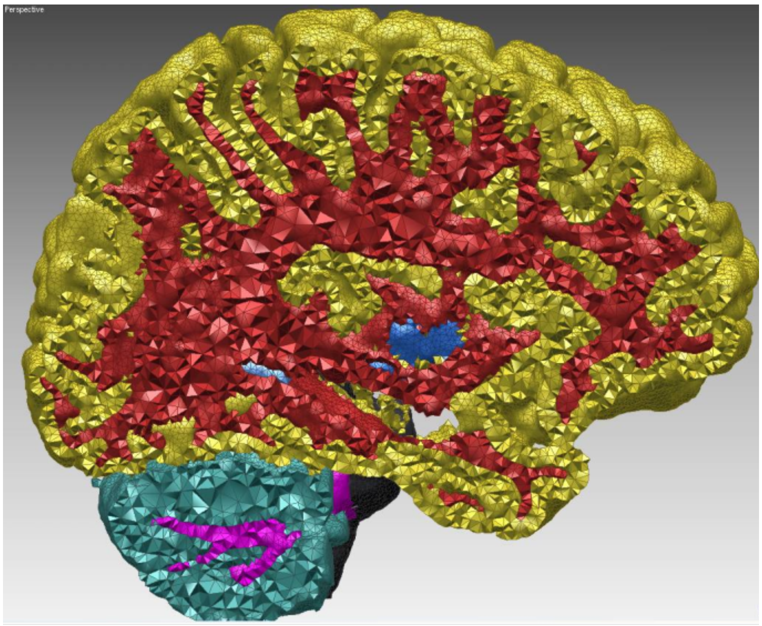

Figure 8. Mesh of a multilabel domain

6.5.3. Delaunay Deformable Models: Topology-Adaptive Meshes Based on the Restricted Delaunay Triangulation

Participant: Jean-Daniel Boissonnat.

In collaboration with Jean-Philippe Pons from CERTIS, École Nationale des Ponts et Chaussées.

In [43], we propose a robust and efficient Lagrangian approach, which we call *Delaunay Deformable Models*, for modeling moving surfaces undergoing large deformations and topology changes. Our work uses the concept of restricted Delaunay triangulation. In our approach, the interface is represented by a triangular mesh embedded in the Delaunay tetrahedralization of interface points. The mesh is iteratively updated by computing the restricted Delaunay triangulation of the deformed objects. Our method has many advantages over popular Eulerian techniques such as the level set method and over hybrid Eulerian-Lagrangian techniques such as the particle level set method: localization accuracy, adaptive resolution, ability to track properties associated to the interface, seamless handling of triple junctions. Our work brings a rigorous and efficient alternative to existing topology-adaptive mesh techniques such as T-snakes.

6.5.4. Interleaving Delaunay Refinement and Optimization for 2D Triangle Mesh Generation

Participants: Jane Tournois, Pierre Alliez, Olivier Devillers.

We address the problem of generating 2D quality triangle meshes from a set of constraints provided as a planar straight line graph [48]. The algorithm first computes a constrained Delaunay triangulation of the input set of constraints, then interleaves Delaunay refinement and optimization. The refinement stage inserts a subset of the Voronoi vertices and midpoints of constrained edges as Steiner points. The optimization stage optimizes the shape of the triangles through the Lloyd iteration applied to Steiner points both in 1D along constrained edges and in 2D after computing the bounded Voronoi diagram. Our experiments show that the proposed algorithm inserts fewer Steiner points than Delaunay refinement alone, and improves over the mesh quality.

6.5.5. *Mesh Sizing with Additively Weighted Voronoi Diagrams*

Participants: Lakulish Antani, Christophe Delage, Pierre Alliez.

We address the problem of generating mesh sizing functions from a set of points with specified sizing values [31]. The sizing functions are shown to be maximal and K-Lipschitz, with arbitrary parameter K provided by the user. These properties allow generating low complexity meshes with adjustable gradation. After constructing an additively weighted Voronoi diagram, our algorithm provides fast and accurate answers to arbitrary point queries. We have implemented our mesh sizing technique as a sizing criterion for the 2D triangle meshing component from the CGAL library. We demonstrate the performance advantages of our technique through experimental results on various inputs.

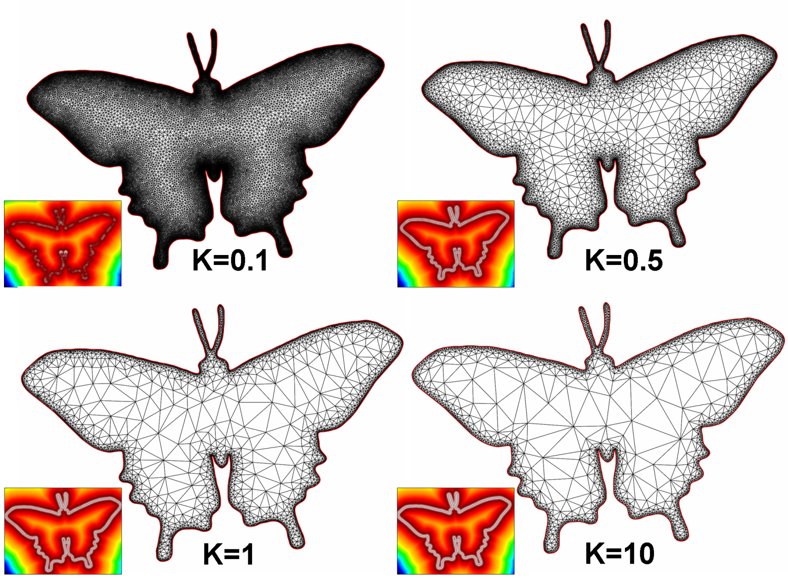

Figure 9. 2D K-Lipschitz mesh sizing with varying parameter K.

6.5.6. *Quadrangle Surface Tiling through Contouring*

Participant: Pierre Alliez.

Our algorithm computes two piecewise smooth harmonic scalar functions, whose isolines tile the input surface into well-shaped quadrangles, without any T-junctions. Our main contribution is an extension of the discrete Laplace operator which encompasses several types of line singularities [28]. The resulting two discrete differential 1-forms are either regular, opposite or switched along the singularity graph edges. We show that this modification guarantees the continuity of the union of isolines across the lines, while the locations of the isolines themselves depend on the global solution to the modified Laplace equation over the whole surface.

6.6. Software

Keywords: *C++ standardization*, *CGAL*, *Python*, *arithmetic filters*, *automatic code generator*.

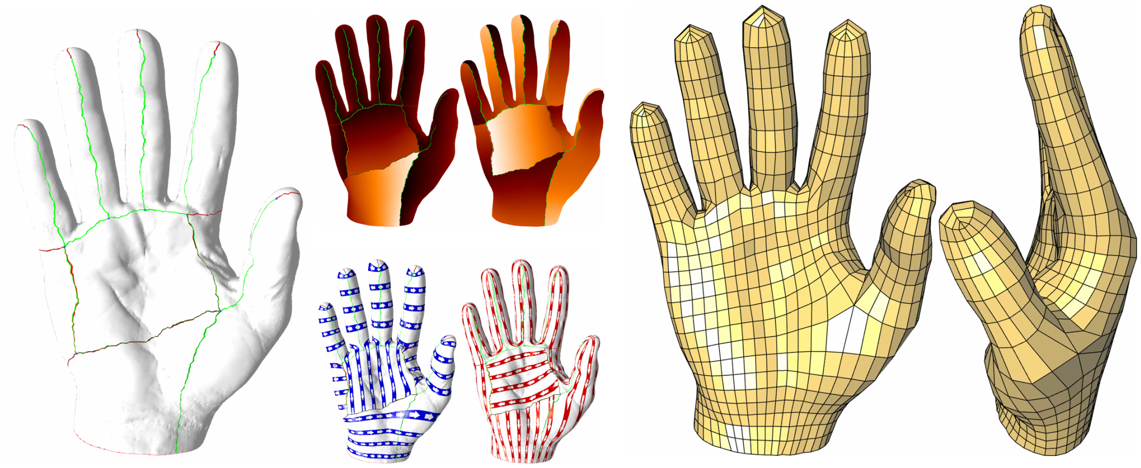

Figure 10. Quadrangle surface tiling. Left: Input surface triangle mesh and singularity graph. Middle: Harmonic functions and associated one-forms. Right: Output quadrangle mesh.

6.6.1. CGAL Release 3.3

A new major release of CGAL, version 3.3, has been made available in June, followed by a bug-fix release version 3.3.1 in September. This release contains the following new packages implemented by GEOMETRICA:

- Spatial Sorting,
- Estimation of Local Differential Properties,
- Approximation of Ridges and Umbilics on Triangulated Surface Meshes.

In addition, other new packages implemented by our CGAL partners are: Skin Surfaces Meshing, Algebraic Foundations, Surface Mesh Simplification, Envelopes of Curves in 2D, Envelopes of Surfaces in 3D, Minkowski Sums in 2D, Linear and Quadratic Programming Solver.

It also contains improvements to some existing packages, the detailed list of which can be found on the CGAL web site.

6.6.2. CGAL-PYTHON: PYTHON bindings around CGAL

Participant: Sylvain Pion.

PYTHON is a powerful, general purpose, interpreted language, which is increasingly used in scientific areas such as molecular biology, and various application areas. It provides bindings around several CGAL packages: 2D and 3D triangulations, Delaunay triangulations, 2D constrained triangulations, 2D mesh generator, 2D and 3D Alpha shapes, 3D Polyhedron, 2D convex hull, several geometric optimization algorithms, and the 2D and 3D kernel. CGAL-PYTHON is available under the Open Source LGPL license, and is subject to the constraints of the underlying CGAL packages. The web site is http://cgal-python.gforge.inria.fr/.

We have released a new version 0.9.3 of the PYTHON wrappers for CGAL in November, which follows the latest release 3.3 of CGAL. No other feature has been added, except porting it to the Mac OS X platform.

6.6.3. C++ standardization of interval arithmetic

Participants: Sylvain Pion, Jihun Yu.

In collaboration with G. Melquiond (Mathematical Components, MSR-INRIA).

We have continued working on a revision of our proposal of specification of interval arithmetic to the C++ standardization committee. We hope that by having this tool standardized, better and faster implementations will exist, and we also hope that certified computations will be considered by more programmers. Some industry members of the C++ standardization committee like Sun Microsystems are also very interested in getting interval arithmetic standardized.

Our proposal is a basic template class parameterized by a floating point type, and provides some functions around it. Due to implementation cost constraints, we had to make choices between the simplicity of the implementation, and functionality. This appears for example in the choice we made for the specification of comparison operators between intervals. An accompanying proposal has also been drafted in the process, specifying the interface for doing multi-valued logic. We have presented our proposals in front of the C++ standardization committee (ISO WG21), where they received good support so far. Since the committee is actively focussed on the next C++ standard C++0x, which will not contain our proposal, we are targetting the next boat, named TR2, which gives us more time to polish the proposal.

This year, we have focussed on providing an implementation of the proposal, which is a critical part of the work to be done to convince the committee and get feedback from early testers. It is based on the Boost.Interval library, which it also means to replace in the long run. The arithmetic part is based on the CRLIBM and MPFR libraries which provide directed rounding for many standard mathematical functions. The implementation and the current draft of the proposal are available at http://gforge.inria.fr/projects/std-interval/.

7. Contracts and Grants with Industry

7.1. GeometryFactory

The initial development phase of the CGAL library has been made by a European consortium. In order to achieve the transfer and diffusion of CGAL in the industry, a company called GEOMETRY FACTORY has been founded in January 2003 by Andreas Fabri (http://www.GeometryFactory.com).

The goal of this company is to pursue the development of the library and to offer services in connection with CGAL (maintenance, support, teaching, advice). GEOMETRY FACTORY is a link between the researchers from the computational geometry community and the industrial users.

It offers licenses to interested companies, and provides support. There are contracts in various domains such as CAD/CAM, medical applications, GIS, computer vision...

GEOMETRY FACTORY is keeping close contacts with the original consortium members, and in particular with GEOMETRICA.

7.2. Alcatel Alenia Space

Participants: Jean-Daniel Boissonnat, Trung Nguyen.

In collaboration with F. Falzon and Guillaume perrin (Thalès Alenia Space).

The goal of this study is to optimize pupil configurations for extended source imaging based on optical interferometry.

The motivation for this work comes from the observation of the Earth from a geostationary orbit (i.e. at a distance of $\sim$ 36000 km) with a resolution of 1 m. A simple calculus shows us that we would need a telescope having a diameter of approximately 20 m for an optical wavelength of $\sim$ 500 nm. Needless to say such an instrument dimension is not adapted to the observation from space and the use of interferometric telescopes (Optical Aperture Synthesis, OAS) is to be considered in this case. We pursue a geometric approach.

7.3. France-Telecom

Participants: Olivier Devillers, Laurent Rineau, Mariette Yvinec.

In collaboration with Jean-François Morlier (France Telecom).

The goal of this study is to compute an abstract representation of an antenna network for mobile phone using Voronoi diagrams. The project ends in december 2007.

7.4. Dassault Systèmes

Participants: Frédéric Chazal, Nicolas Montana.

In collaboration with Andre Lieutier (Dassault systemes)

The goal of this study is to develop and implement robust and efficient 3D Boolean operators and surface regularization tools for industrial use.

The motivation of this work comes from machining simulation where the computation of the part of the space sweeped by a moving tool involve a huge amount of boolean operations (unions, intersections, differences). Such computations meets two main difficulties (that are both theoretical and technical): first 3D boolean operations face robustness issues and second, the output of large sequences of Boolean operations usually consists of very complicated meshes containing many irrelevant topological and geometric features that need to be removed for further processings. In this study, we intend to develop a software based on an original theoretical approach that overcome these difficulties.

8. Other Grants and Activities

8.1. National initiatives

8.1.1. ANR Triangles

Participants: Manuel Caroli, Pedro Machado Manhães de Castro, Olivier Devillers, Sylvain Pion, Monique Teillaud.

http://www-sop.inria.fr/geometrica/collaborations/triangles/

We lead the TRIANGLES project funded by the ANR. The project involves
— the «Laboratoire d'InfoRmatique en Image et Systèmes d'information» (LIRIS), Lyon,
— the «Département d'informatique de l'ENS» and
— the GEOMETRICA team.

Triangulations are essential by their applications in particular for meshing and shape reconstruction. We want to develop and distribute new results for academic and industrial researchers. The goal of the project is the development of robust and effective algorithms for the manipulaion of large sets of points, of mobile sets of points and points in non Euclidean spaces such as periodic spaces (torus, cylinder), projective, oriented projective or hyperbolic spaces. The results obtained will be coded using CGAL library and will be applied in the vision (visual envelopes, calibration of camera), fluid dynamics, astronomy, computer graphics or for medical applications.

In the GEOMETRICA team, Triangles is co-funding the scolarship of Pedro de Castro (with «Région PACA») and funding traveling and computers. The first project meeting was in Lyon on december 6th.

- Starting date : november 2007

- Duration : 3 years

8.1.2. ANR GAIA

Participants: Jean-Daniel Boissonnat, Frédéric Chazal, David Cohen-Steiner.

The aim of this project is to formalize a collaboration between researchers from computational geometry, machine learning and computer vision to study distortions and in particular Bregman divergences, information theory, statistics, Riemannian geometry, and convex analysis.

The other partners of the project are the Université des Antilles et de la Guyane (R. Nock, coordinator), the Ecole Polytechnique (F. Nielsen), the Lear project-team (C. Schmid).

- Starting date : november 2007

- Duration : 4 years

8.1.3. ANR GeoTopAl

Participants: Pierre Alliez, Jean-Daniel Boissonnat, Frédéric Chazal, David Cohen-Steiner, Sylvain Pion.

This project aims at developing concepts, methods and algorithms for solving problems in the realm of geometric modeling (of complex shapes), reverse engineering and numerical simulation, as well as visualization. The concepts and methods sought after should be rich enough to accommodate a certain mathematical sophistication, while remaining compatible with the constraints inherent to the development of efficient and certified algorithms. (Certification herein refers to a geometric and topological coherence between the input and the output of an algorithm.) Meeting these two goals simultaneously requires a close collaboration between Mathematics —Differential Topology and Geometry, and Computer Science —Computational Geometry and Solid Modeling. Bridging the gap between these disciplines is not traditional and contributes to the main innovative aspect of this project. The goals pursued cover theoretical and applied aspects. On the one hand, the project aims at developing a mathematical theory for geometric and topological approximation. On the other hand, implementation and efficiency issues of algorithms will also be addressed. In particular, algorithms will be validated on a fairly large spectrum of applications involving 3D models in the scope of Digital Geometry Processing.

This project coordinated by Geometrica also involves researchers from the INRIA team-project ABS, CNRS (Grenoble, ENS Paris), and a representative from the industry holding a PAST position (Visiting Professor from Industry) at the university of Grenoble.

8.1.4. ANR Gyroviz

Participants: Pierre Alliez, Jean-Daniel Boissonnat, Nader Salman, Mariette Yvinec.

The project Gyroviz was selected by the ANR in the framework of the call Audivisual and Multimedia techniques. The project involves the SME Sofresud (Toulon, coordinator) and IXSEA and research teams from the CEA, INRIA and SupMECA Toulon. The project addresses the challenge of automatic modeling of 3D physical scenes from located frames. The aim of the project is to couple new accurate inertial sensors with an image acquisition device and efficient reconstruction softwares to build a performant image-based modeling system with no required human interaction.

- Starting date : december 2007

- Duration : 3 years

8.1.5. ACI Geocomp

Participants: Pierre Alliez, Olivier Devillers, Abdelkrim Mebarki.

http://www.lix.polytechnique.fr/Labo/Gilles.Schaeffer/GeoComp/

We are a member of GEOCOMP an initiative from the national «Action Concertée Incitative Masses de Données». The project involves
— the «Laboratoire d'Informatique de l'Ecole Polytechnique (LIX), CNRS, Ecole Polytechnique»,
— the «Laboratoire Bordelais de Recherche en Informatique (LaBRI), CNRS, Université Bordeaux I»,
— the «Service de Physique Théorique, CEA Saclay» and
— the GEOMETRICA team.

The project investigates compression schemes and compact data structures devoted specifically to geometrical objects and terminates this year.

- Starting date : july 2004

- Duration : 3 years

8.1.6. Color

Participant: Mariette Yvinec.

The MEDMESH color involves the teams Geometrica, Asclépios, Caiman and Odyssée from INRIA Sophia Antipolis and the Neurophysiology and Neuropsychology Laboratory of the hospital *La Timone* in Marseille. The goal is to test the mesh generator developped in Geometrica on real meshing problems provided by the other teams of the Color.

The web site of the color Medmesh is at the url: http://www-sop.inria.fr/geometrica/collaborations/Medmesh.

8.2. European initiatives

8.2.1. STREP FET Open ACS

Participants: Jean-Daniel Boissonnat, Andreas Meyer, Sylvain Pion, Laurent Rineau, Monique Teillaud, Camille Wormser, Mariette Yvinec.

In collaboration with FrédéricCazals, member of the equipe-projet ABS.

INRIA (project-teams GALAAD, GEOMETRICA and ABS) participates to the IST project ACS.
– Acronym : ACS, IST-006413
– Title : Algorithms for complex shapes with certified topology and numerics.
– Specific program : IST
– STREP (FET Open)
– Starting date : may 1st, 2005 - Duration : 3 years
– Participation mode of INRIA : Participant
– Other participants : Rijksuniversiteit Groningen, Eidgenössische Technische Hochschule Zürich, Freie Universität Berlin, Institut National de Recherche en Informatique et Automatique, Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V., National Kapodistrian University of Athens, Tel Aviv University, GeometryFactory Sarl
The ACS project aims at advancing the state of the art in computing with complex shapes. Current technology can cope well with curves in the plane and smooth surfaces in three-dimensional space. We want to address a larger class of shapes, including piecewise smooth surfaces, surfaces with singularities, as well as manifolds of codimension larger than one in moderately high dimension.

Increasingly demanding applications require efficient and robust algorithms for complex shapes. Topics that arise and that we address are shape approximation (including meshing and simplification), shape learning (including reconstruction and feature extraction), as well as robust modeling (including boolean operations). Our work on these topics will be closely intertwined with basic research on shape representations.

A unique and ambitious feature of our approach is the guaranteed quality of all data structures and algorithms we plan to develop. Through certified topology and numerics, we will be able to prove that the output is topologically and numerically consistent, according to prespecified criteria. A software prototype, dealing with a restricted class of complex shapes, will demonstrate the feasibility of our techniques in practice.

The web site of the project includes a detailled description of the objectives and all results. See http://acs.cs.rug.nl.

8.2.2. Network of Excellence AIM@SHAPE

Participants: Pierre Alliez, Jean-Daniel Boissonnat, Sylvain Pion, Laurent Saboret, Mariette Yvinec.

INRIA is part of the Network of Excellence:
– Acronym : AIM@SHAPE
– Title: Advanced and Innovative Models And Tools for the development of Semantic-based systems for Handling, Acquiring, and Processing Knowledge Embedded in multidimensional digital objects).
– Reference: 506766
– Start Date: 2004-01-01

– Duration: 48 months
– Contract Type: Network of Excellence
– Action Line: Semantic-based knowledge systems
– Project Funding: 5.74 Million Euros.
– Other participants :
– IMATI, Genova, Italy.
– University of Genova, Italy.
– EPFL, Lausanne, Switzerland.
– Fraunhofer Institute, Germany.
– INPG, France.
– Center for Research and Technology, Greece.
– University of Geneva, Switzerland.
– SINTEF, Norway.
– TECHNION, Israel.
– Weizmann Institute, Israel.
– Utrecht University, Netherlands.

The mission of AIM@SHAPE is to advance research in the field of semantic-based shape representations and semantic-oriented tools to acquire, build, transmit, and process shapes with their associated knowledge. We foresee a generation of shapes in which knowledge is explicitly represented and, therefore, can be retrieved, processed, shared, and exploited to construct new knowledge. The attainment of a new vision of shape knowledge is achieved by: the formalisation of shape knowledge and the definition of shape ontologies in specific contexts; the definition of shape behaviours which formalise the interoperability between shapes; the delineation of methods for knowledge-based design of shapes and the definition of tools for semantics-dependent mapping of shapes. The web site of the network includes a detailled description of the objectives and some results.

Network web pages : http://www.aim-at-shape.net.

8.3. International initiatives

8.3.1. Associated team Genepi

Participants: Sylvain Pion, Monique Teillaud.

We are involved in an INRIA associated team with Chee Yap (New York University) around the subjects of generic programming and robustness of geometric algorithms. This work includes the specification of algorithms in terms of concepts of geometries. It also includes the interface between algorithms and data structures, as well as collaborations on robustness issues when dealing with curved objects.

8.3.2. Associated team Geotech

Participants: Pierre Alliez, Jean-Daniel Boissonnat, Mariette Yvinec, Camille Wormser.

Starting from beginning of 2007 we have established an INRIA associated team with Craig Gotsman, Gill Barequet and Ayellet Tal from Technion, Israel. Our goal is to collaborate on topics commonly referred to as Geometry Processing. More specifically, we exchange ideas and software on surface reconstruction, geometric routing, quadrangle surface tiling and shape matching.

8.3.3. Scientific and Technological Cooperation between France and Israel

Participants: Jean-Daniel Boissonnat, David Cohen-Steiner, Mariette Yvinec.

In the framework of the Research Networks Program in Medical and Biological Imaging from the High Council for Scientific and Technological Cooperation between France-Israel, we have obtained a financial support for the following project *Geometric reconstruction of organs from freehand ultrasound*. Our israelian partner is the Technion-Israel Institute of Technology, located in Haifa.

8.3.4. Partenariat Hubert Curien Amadeus with Austria

Participants: Manuel Caroli, Olivier Devillers, Monique Teillaud [coordinator].

http://www-sop.inria.fr/geometrica/collaborations/Amadeus/index.html

This PHC *"Geometric concepts and* CGAL*"* started in 2007. It is a cooperation with the Institute for Software Technology at Graz University of Technology. Several visits were organized.

9. Dissemination

9.1. Animation of the scientific community

9.1.1. Editorial boards of scientific journals

- J-D. Boissonnat is a member of the editorial board of *Discrete and Computational Geometry*, *Algorithmica* and the *International Journal of Computational Geometry and Applications*. He is also on the editorial board of new Springer Verlag book series on Geometry and Computing.
- M. Yvinec is a member of the editorial board of *Journal of Discrete Algorithms*.
- S. Pion (chair), M. Teillaud and M. Yvinec are members of the CGAL editorial board.
- P. Alliez is a member of the editorial board of *The Visual Computer* and *Computers & Graphics*.

9.1.2. Conference program committees

- Pierre Alliez was a member of the program committee of SIGGRAPH, CAD/Graphics, Pacific Graphics, Shape Modeling International, ACM Symposium on Solid and Physical Modeling, EUROGRAPHICS Symposium on Geometry Processing.

- Jean-Daniel Boissonnat was a member of the program committee of the EUROGRAPHICS Symposium on Geometry Processing.

- David Cohen-Steiner was a member of the program committees of ACM Symposium on Computational Geometry and EUROGRAPHICS Symposium on Geometry Processing.

- Olivier Devillers was a member of the program committee of DGCI'08, 14th Discrete Geometry and Computer Imagery.

- Monique Teillaud was the Video/Multimedia committee chair of SoCG'07, 23rd Annual Symposium on Computational Geometry.

9.1.3. Ph.D. thesis and HDR committees

– Jean-Daniel Boissonnat was a member of the HDR committees of Fabrice Rouillier, Sylvain Lazard, Monique Teillaud, Sylvain Petitjean, and member of the PhD committees of Dobrina Boltcheva (LSIIT-IRCAD) and Laurent Rineau.
— Olivier Devillers was a member of the HDR committee of David Coeurjolly, Lyon, 2007
— Monique Teillaud was a member of both the oral and written PhD committees of Daniel Russel, Stanford University, January 16, 2007.

9.1.4. INRIA committees

- Pierre Alliez is member of the « Comité des cours et colloques » at INRIA Sophia-Antipolis.
- Agnès Bessière is member of the « Comité des utilisateurs des moyens informatiques des services de l'INRIA Sophia-Antipolis » (CUMIS)
- Pierre Alliez, Agnès Bessière and Olivier Devillers are members of the « comité de centre » at INRIA Sophia-Antipolis.
- Jean-Daniel Boissonnat is chairman of the INRIA Evaluation Board.
- Olivier Devillers is « Chargé de mission » about the usage of geometry in communication networks.
- Sylvain Pion was a member of the « Commission du Développement Logiciel » (CDL) at INRIA Sophia-Antipolis, until March.

- Monique Teillaud is a member of the INRIA Evaluation Board, the INRIA Sophia Antipolis Color (COopérations LOcales de Recherche) Commission, and the INRIA Sophia Antipolis Commission for Hygiene and Security. She is a member of the INRIA Sophia Antipolis « Comité de Suivi Doctoral » since november.
- Mariette Yvinec is member of the « Comité des utilisateurs des moyens informatiques de recherche de l'INRIA Sophia-Antipolis » (CUMIR)

9.1.5. Other committees

- Jean-Daniel Boissonnat is member of the « Commission de spécialistes » of the Ecole Normale Supérieure de Paris.
- Frédéric Chazal was member of the « Commission de spécialistes » of the Mathematics Department of the University of Bourgogne, Dijon, France until september 1st.
- Sylvain Pion is member of the experts group of AFNOR for the C++ language.
- Monique Teillaud served in the evaluation committee of the «Doktorats Kolleg» "Computational Mathematics: Numerical Analysis and Symbolic Computation" for the Austrian Science Fundation.

9.1.6. Conference organization

- Olivier Devillers organized the 2007 edition of the «Journées Informatique et Géométrie» http://www-sop.inria.fr/geometrica/events/jig2007/

- Monique Teillaud organized the Workshop on Robust Shape Operations, September 26-28, 2007. There were 46 participants. Fabrice Rouillier (INRIA SALSA) and Chee Yap (New York University) gave invited talks. The workshop was partially sponsored by the STREP ACS, the associated team Genepi, and the GDR Informatique Mathématique. The administrative organization was undertaken by Agnès Bessière.
http://www-sop.inria.fr/geometrica/events/WRSO/.

- Frédéric Chazal and David Cohen-Steiner co-organized with M. Aupetit (CEA) and G. Gasso (INSA Rouen) a workshop at the Neural Information Processing Systems Conference 2007 (Vancouver) on "New challenges at the crossing of Machine Learning, Computational Geometry and Topology".

- Mariette Yvinec organized the 26th CGAL Developer Meeting, Feb 5-9 2007, at INRIA Sophia Antipolis.

- Sylvain Pion co-organized with Andreas Fabri (GeometryFactory) the CGAL day in Beijing, China, during the 10th anniversary of the LIAMA, January 19th 2007.

9.2. Teaching

9.2.1. Teaching responsibilities

- In the «Master STIC» of Nice Sophia-Antipolis University Olivier Devillers chairs the second year research speciality : «Image et géométrie pour le multimédia et la modélisation du vivant»
- Olivier Devillers is professor «Chargé de cours» at École Polytechnique.
- Sylvain Pion is a member of the admission jury at the ENS.

9.2.2. Teaching at universities

- Cours du Diplôme d'Informatique de l'ENS (2006-2007), Introduction au calcul scientifique et ses applications - Calcul géométrique certifié, Monique Teillaud (2h).
- MPRI (Master Parisien de Recherches Informatiques) (2006-2007), Cours de 2ième annee , Objet fondamentaux de la géométrie algorithmique, Introduction à l'approximation géométrique et topologique, Frédéric Chazal (9h).
- Maîtrise Informatique (2006-2007) (Nice), Computational Geometry, 24h (O. Devillers 12h, A. Mebarki 12h).
- Master STIC-IGMMV-ISI (Sophia-Antipolis), Research Initiation in Images and Geometry (2007-2008) 9h, (P. Alliez, O. Devillers and M. Teillaud).

- MPRI (Master Parisien de Recherches Informatiques) (2007-2008), Cours de 2ième annee , Géométrie algorithmique : Diagrammes de Voronoï, Triangulations et Maillages, Jean-Daniel Boissonnat and Mariette Yvinec (24h).
- MPRI (Master Parisien de Recherches Informatiques) (2007-2008), Cours de 2ième annee , Objet fondamentaux de la géométrie algorithmique, Introduction à l'approximation géométrique et topologique, Frédéric Chazal (9h).
- École Polytechnique (Palaiseau), Computational Geometry (2007-2008), 40h (O. Devillers).
- École Polytechnique (Palaiseau), Java programming (2007-2008), exams (O. Devillers).

9.2.3. Internships

Internship proposals can be found on the web at http://www-sop.inria.fr/geometrica/positions/
- Mridul Aanjaneya, *Triangulations in the Projective Plane*, IIT Kharagpur.
- Antoine Bru, *3D cellular complexes in* CGAL, Master 1, University Pierre et Marie Curie.
- Manuel Caroli, *Triangulations in Periodic Spaces*, Master 2, Saarland University.
- Ankit Gupta, *Principal Component Analysis in CGAL, and convergence analysis of a Voronoi-PCA normal estimator*, IIT Bombay.
- Dave Millman, *Parallel computation of the 3D Delaunay triangulation in* CGAL, New York University.
- Emmanuel Olivi, *Quantitative comparisons of forward problem in EEG* [60], INSA de Toulouse.
- Jihun Yu, *Implementation of the proposal for standardization of interval arithmetic in C++*, New York University.

9.2.4. Ongoing Ph.D. theses

- Manuel Caroli, *New Spaces for Computational Geometry*, université de Nice-Sophia Antipolis.
- Pedro Machado Manhães de Castro, *Triangulating sets of moving points*, université de Nice-Sophia Antipolis.
- Abdelkrim Mebarki, *Structures de données compactes pour la géométrie*, université de Nice-Sophia Antipolis.
- Pooran Memari, *Reconstruction from unorganized cross-sections*, université de Nice-Sophia Antipolis.
- Quentin Mérigot, *Détection de structures géométriques dans les nuages de points*, université de Nice-Sophia Antipolis.
- Nicolas Montana, *Calcul robuste d'enveloppes de solides en mouvement. Application à la simulation de l'enlèvement de matière en usinage*, Université Paris-Sud et Dassault Systèmes.
- Thanh-Trung Nguyen, *Geometric Optimization for the Conception of Telescopes*, université de Nice-Sophia Antipolis.
- Nader Salman, *Reconstruction de surfaces lisses par morceaux*, université de Nice-Sophia Antipolis
- Jane Tournois, *Maillages optimisés*, université de Nice-Sophia Antipolis.
- Camille Wormser, *Maillages et diagrammes anisotropes*, université de Nice-Sophia Antipolis.

9.2.5. Ph.D. and HDR defenses

- Monique Teillaud – Computational geometry – From theory to practice, From linear objects to curved objects. Habilitation à diriger des recherches, Université de Nice Sophia Antipolis, September 25, 2007 [15].
- Laurent Rineau, *Maillages de volumes bornés par des surfaces lisses par morceaux*. Ph.D. defense, Université de Paris VI, November 30, 2007 [13].
- Marie Samozino – *Voronoi Centered Radial Basis Functions*. Ph.D. defense, Université de Nice Sophia Antipolis, July 11, 2007 [14].

9.3. Participation to conferences, seminars, invitations

9.3.1. Invited Talks

- Pierre Alliez, "Variational Shape Reconstruction". Shape Modeling International, June 13-15, 2007.
- Pierre Alliez, "Quadrangle Surface Tiling through Contouring". Polyhedral Surfaces and Industrial Applications, Strobl, September 15-18, 2007. 12th Conference on the Mathematics of Surfaces, Sheffield, 4-6 Sep 2007.

- Pierre Alliez, “Variational Shape Reconstruction”. Polyhedral Surfaces and Industrial Applications, Strobl, September 15-18, 2007.
- Jean-Daniel Boissonnat, "Bregman diagrams and triangulations", Topology Learning NIPS 2007 workshop.
- Frédéric Chazal, “Sampling and Topological Inference For General Shapes”, Workshop on Geometric and Topological Approaches to Data Analysis, TTI Chicago, October 2007.
- Frédéric Chazal, “A Sampling Theory for Compact Sets in Euclidean Space”, workshop on Discrete geometry and topology in low dimensions, Banff (Canada), April 2007.
- David Cohen-Steiner, “Topological persistence”, MFO Oberwolfach workshop “Trends in Mathematical Imaging and Surface Processing”, April 2007.
- David Cohen-Steiner, “Stability of Boundary Measures”, workshop on discrete geometry and topology in low dimensions, Banff (Canada), April 2007.
- David Cohen-Steiner, “Stability of Boundary Measures”, Discrete Differential Geometry Conference, Harnack Haus (Berlin), July 2007.
- David Cohen-Steiner, “Stability of Boundary Measures”, Workshop on Geometric and Topological Approaches to Data Analysis, TTI Chicago, November 2007.
- Sylvain Pion, "Aspects Logiciels dans la Recherche en Géométrie Algorithmique", Les journées informatiques X-UPS, Ecole Polytechnique, May 2007.

9.3.2. Conferences and Seminars

Members of the project have presented their published articles at conferences. The reader can refer to the bibliography to obtain the corresponding list. We list below all other talks given in seminars or summer schools.
- Pierre Alliez, «Geometry Processing». AIMSHAPE summer school, Genova, June 2007.
- Pierre Alliez, “Geometric Modeling Based on Polygonal Meshes ”. SIGGRAPH course, San Diego, August, 2007.
- Frédéric Chazal, “Inférence et stabilité topologique de formes à partir d’approximations”, Journées de l’Association Française d’Approximation, Paris, November 2007. - Olivier Devillers, «Random sampling of a cylinder yields a not so nasty Delaunay triangulation», Vegas-INRIA-Lorraine seminar. July 2007
- Olivier Devillers, «Between umbra and penumbra», Graz computational geometry seminar. December 2007
- Monique Teillaud, «Calcul exact et efficace sur les arcs de cercles dans la bibliothèque CGAL», Journées Nationales de Calcul Formel, January 2007.
- Monique Teillaud, «Design of the CGAL 3D Spherical Kernel», Dagstuhl Seminar on Computational geometry, March 2007.

9.3.3. The Geometrica seminar

http://www-sop.inria.fr/geometrica/seminars/
The GEOMETRICA seminar featured presentations from the following visiting scientists:
- Michel Barlaud (I3S) : High-dimensional statistical measure framework for region-of-interest tracking
- Jean-Philippe Pons (CERTIS) : Shape reconstruction from images using Delaunay meshing: some recent results.
- Oswin Aichholzer et Birgit Vogtenhuber (TU Graz) : Maximizing Maximal Angles for Plane Straight-Line Graphs.
- Guillaume Melquiond (ENS Lyon, LIP) : De l’arithmétique d’intervalles à la certification de programmes.
- Tamal Dey (Ohio State U.) : On computing handles and tunnels in a shape.
- Xavier Descombes (INRIA, Ariana) : Marked Point Processes in Images Analysis : from context to geometry.
- Patrick Laug (GAMMA) : Maillages déformables et maillages de surfaces paramétrées.
- Francois Faure (IMAG) : Interactive mechanical simulation of biological models using regular hexahedral FEM.
- Eitan Yaffe (TAU) : Efficient Identification of Pathways in the Complement of the Union of Balls in R3.
- Sylvain Lefebvre : (INRIA REVES) : Appearance-Space Texture Synthesis.
- Anne-Marie Kermarrec (ASAP/IRISA) : Querying peer to peer systems efficiently.
- Christian Roessl (INRIA Geometrica) : Animation Collage.
- Marc Eastlick (industriel) : Discrete differential geometry and example applications.

- Joachim Giesen (Saarbruecken) : Medial axis approximation and unstable flow complex.
- Jean-Philippe Pons (ENPC) : Shape reconstruction from images using some recent Delaunay-based algorithms.
- Bruno Pelletier (Montpellier) : Quelques problèmes d'inférence statistique sur des variétés.

9.3.4. Scientific visits

- Monique Teillaud, Manuel Caroli and Olivier Devillers visited the Institute for Software Technology at Graz University of Technology respectively in July, November and December.
- David Cohen-Steiner visited the Technische Universität Berlin for a few days in October 2007.
- Frédéric Chazal visited the Toyota Technological Institute (Prof. S. Smale) for a few days in October 2007.
- Olivier Devillers visited EPI-ASAP in july, EPI-VEGAS in july and november.

9.3.5. Distinctions

- Pierre Alliez and David Cohen-Steiner: Best paper award at the fifth EUROGRAPHICS Symposium on Geometry Processing. July 2007.
- Pierre Alliez and Christian Rössl: SIGGRAPH NVIDIA award for the best course notes. August 2007.

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[14] M. SAMOZINO. *Voronoi Centered Radial Basis Functions*, Thèse de doctorat en sciences, université Nice Sophia-Antipolis, Nice, France, 2007.

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