INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team geometrica

Geometric Computing

Sophia Antipolis

THEME 2B

Activity Report

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2. Overall Objectives

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 optimisation. However, in the mid-nineties, it was recognized that the applicability in practice of the 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 towards a standard for safe and effective geometric computing.

3. Scientific Foundations

3.1. Introduction

The research conducted by GEOMETRICA focuses on three main directions:
- design and analysis of geometric algorithms for curves, surfaces and triangulations
- robust computation and advanced programming,
- shape approximation, surface reconstruction and compression.

3.2. Geometric algorithms for curves, surfaces and triangulations

GEOMETRICA intends to revisit the field of computational geometry in order to understand how structures that are well-known for linear objects behave when defined on curves and surfaces. We are especially interested in extending the theory of Voronoi diagrams beyond the affine case. This research includes to study the mathematical properties of these structures and to design algorithms to construct them. To ensure the effectiveness of our algorithms, we precisely specify what are the basic numerical primitives that need to be performed, and consider tradeoffs between the complexity of the algorithms (i.e. the number of primitive calls), and the complexity of the primitives and their numerical stability. Working out carefully the robustness issues is a central objective of GEOMETRICA (see below).

Decomposing a complex shape in basic simple elements such as triangles or tetrahedra is a first step for many purposes, starting from visualization and going to more complex modeling such as meshing for finite elements method. *Triangulations* are a fundamental structure in this respect. Triangulations and, in particular, Delaunay triangulations have been extensively studied by the Computational Geometry community: the algorithmic and combinatorial issues are mostly solved in the plane. The situation is different in higher dimensions, and even in three dimensional space, many questions remain open.

A first question is related to the combinatorial complexity of the Delaunay triangulation in 3-dimensional space. It is well known that this size can be quadratic, but examples of such behavior seem quite artificial and work has been done to prove sub-quadratic behaviors under realistic hypotheses.

Constrained triangulations are triangulations that include some given sets of edges and triangles. A typical case is to include the boundary of some polyhedral domain. Computing a constrained triangulation is more difficult than just triangulating a set of points, and it is NP-hard to decide if such a triangulation exists. Adding points to the original set is then required to help triangulating while respecting the constraints or to obtain well shaped tetrahedra. Designing efficient algorithms, with certified results and a controlled number of added points for such purposes is an active area of research GEOMETRICA investigates.

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 output. This is observed in all commercial CAD-systems.

The importance of robustness in geometric computations was 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* and *controlled rounding*.

In addition to pursuing research on robust geometric computation, GEOMETRICA is an active member of a European consortium that develops 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. A startup company has been launched in January 2003 to commercialize components from CGAL and to offer services for geometric applications.

3.4. Shape approximation

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 questions afore-mentioned 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 wants to construct a piece-wise 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 way. 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.

4. Application Domains

4.1. Geometric Modeling and Shape Reconstruction

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

Modeling 3D shapes is required for all visualization applications where interactivity is key 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 help 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, the geometric modeling for simulation having received more attention in recent years due to the increased performance of numerical simulation packages. 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 precise 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. Algorithmic issues in Structural Biology

Key words: *Molecules*, *docking*.

Two of the most prominent challenges of the post-genomic era are to understand the molecular machinery of the cell and to develop new drug design strategies. These key challenges require the determination, understanding and exploitation of the three-dimensional structure of several classes of molecules (nucleic acids, proteins, drugs), as well as the elucidation of the interaction mechanisms between these molecules.

These challenges clearly involve aspects from biology, chemistry, physics, mathematics and computer science. For this latter discipline, while the historical focus has been on text and pattern matching related algorithms, the amount of structural data now available calls for geometric methods. At a macro-scopic scale, the classification of protein shapes, as well as the analysis of molecular complexes requires shape description and matching algorithms. At a finer scale, molecular dynamics and force fields require efficient data-structures to represent solvent models, as well as reliable meshes so as to solve the Poisson-Boltzmann equation.

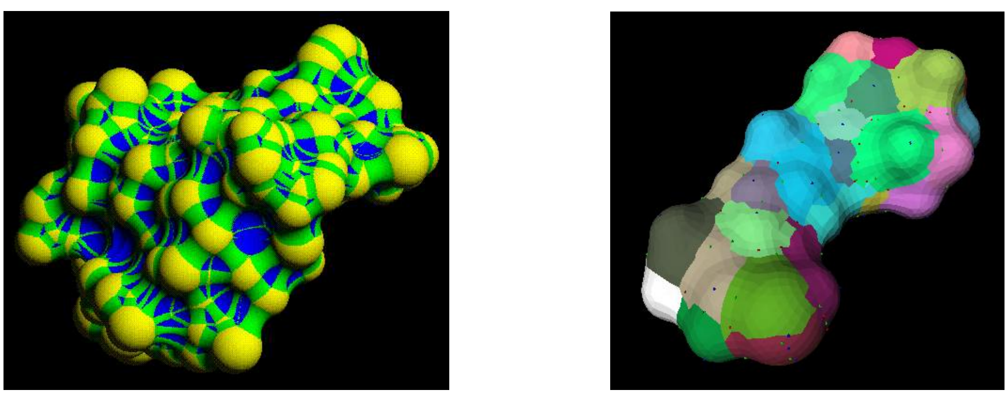

Figure 1. (a) Molecular surface (b) Knobs on a molecular surface (from [50])

4.3. Scientific computing

Key words: *Unstructured meshes*, *finite element method*, *finite volume method*.

Meshes are the basic tools for scientific computation. Unstructured meshes allow to mesh complex shapes and to refine locally the mesh, which may be required because of the geometry or in order to increase the precision of the computation. GEOMETRICA contributes to 2D and 3D meshes, and also to surface meshes. The methods are mostly based on Delaunay triangulations, Voronoi diagrams and their variants. Affine diagrams are well-suited for volume element methods. Non affine diagrams are especially important in the context of anisotropic meshes. Anisotropic quadrilateral meshes are also of interest.

4.4. Telecommunications

Key words: *Compression*.

The emerging demand for visualizing and simulating 3D geometric data in networked environments has motivated research on representations for such data. Slow networks require data compression to reduce the latency, and progressive representations to transform 3D objects into streams manageable by the networks. The members of GEOMETRICA have contributed several original compression methods for surface and volume meshes. We investigate both single-rate and progressive compression depending on whether the model is intended to be decoded during, or only after, the transmission. The case of progressive compression is in fact closely related both to approximation and information theory, aiming for the best trade-off between data size and approximation accuracy (the so-called rate-distortion tradeoff). We now cast this problem into the one of *shape compression*.

5. Software

5.1. cgal, the library of geometric algorithms

Participants: Jean-Daniel Boissonnat, Hervé Brönnimann, Frédéric Cazals, Frank Da, Olivier Devillers, Andreas Fabri, Julia Flötotto, Philippe Guigue, Menelaos Karavelas, Sylvain Pion [contact person], François Rebufat, Monique Teillaud, Radu Ursu, Mariette Yvinec.

CGAL is a C++ library of geometric algorithms developed initially 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. 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 in a kernel, a basic library and a support library. The kernel is made of classes that represent elementary geometric objects (points, vectors, lines, segments, planes, simplices, isothetic boxes...), 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...).

The basic library provides a number of 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...).

GEOMETRICA is particularly involved in the arithmetic issues that arise in the treatment of robustness issues, the kernel, triangulation packages and their close applications such as alpha shapes, general maintainance...

CGAL is about 400,000 lines of code and supports various platforms: GCC (Linux, Solaris, Irix, Cygwin...), MipsPro (IRIX), SunPro (Solaris), Visual C++ (Windows), Intel C++... Version 3.0 has been released on november 6th, 2003. The previous release, CGAL 2.4, has been downloaded 9000 times from our web site, during the 18 months period where it was the main version.

5.2. 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 David Cohen-Steiner and Frank 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 get a first impression of the algorithm to see if it fits the needs, before contacting INRIA for obtaining an executable, learning how to call the program, etc. At the same time it allows us to collect real-world data sets to test and improve our algorithms.

6. New Results

6.1. Combinatorics, data structures and algorithms

6.1.1. The Voronoi diagram of planar convex objects

Participant: Mariette Yvinec.

In collaboration with Menelaos Karavelas, University of Notre Dame (USA).

This work results in a dynamic algorithm for the construction of the Euclidean Voronoi diagram of a set of convex objects in the plane [58][42]. We consider first the Voronoi diagram of smooth convex objects forming pseudo-circles sets. A pseudo-circles set is a set of bounded objects such that the boundaries of any two objects intersect at most twice. The algorithm is a randomized dynamic algorithm. It does not use a conflict graph or any sophisticated data structure to perform conflict detection. This feature allows us to handle deletions in a relatively easy way. In the case where objects do not intersect, the randomized complexity of an insertion or deletion can be shown to be respectively $O(\log^2 n)$ and $O(\log^3 n)$. The algorithm can easily be adapted to the case of pseudo-circles sets formed by piecewise smooth convex objects. Finally, given any set of convex objects in the plane, it is shown how to compute the restriction of the Voronoi diagram in the complement of the objects' union.

6.1.2. Möbius diagrams

Participants: Jean-Daniel Boissonnat, Christophe Delage.

In collaboration with Menelaos Karavelas, University of Notre Dame (USA).

This work is a continuation of the work done last year on Voronoi diagrams of spheres. We introduce a new type of Voronoi diagrams called *Möbius diagram* [60][31] (see Figure 2). They are generalizations of both power diagrams and multiplicatively weighted Voronoi diagrams. We show that computing a Möbius diagram in $\mathbb{R}^{d-1}$ can be reduced to computing a power diagram in $\mathbb{R}^d$. Using this reduction, we show that the worst case complexity of a Möbius diagram for a set of n weighted points in $\mathbb{R}^{d-1}$ is $\Theta(n^{\lceil \frac{d}{2} \rceil})$ and that they can be computed within this time bound. Möbius diagrams can equivalently be defined as Voronoi diagrams with spherical bisectors. It follows that Möbius diagrams are closed under sphere-preserving or Möbius transformations. We also show that Möbius diagrams have a Euclidean model in terms of additively weighted Voronoi cells in $\mathbb{R}^{d+1}$. A consequence is a tight bound on the complexity of : (1) a single additively weighted Voronoi cell in dimension d; (2) the convex hull of a set of d-dimensional spheres. In particular, given a set of n spheres of $\mathbb{R}^d$, we show that the worst case complexity of both a single additively weighted Voronoi cell and the convex hull of the set of spheres is $\Theta(n^{\lceil \frac{d}{2} \rceil})$. The equivalence between additively weighted Voronoi cells, convex hulls of spheres and Möbius diagrams permits us to compute a single additively weighted Voronoi cell in dimension d in worst case optimal time $O(n \log n + n^{\lceil \frac{d}{2} \rceil})$.

The construction of Möbius diagrams in the plane has been implemented [60]. The construction of Apollonius diagrams (or diagrams of spheres) in $\mathbb{R}^3$ is under development.

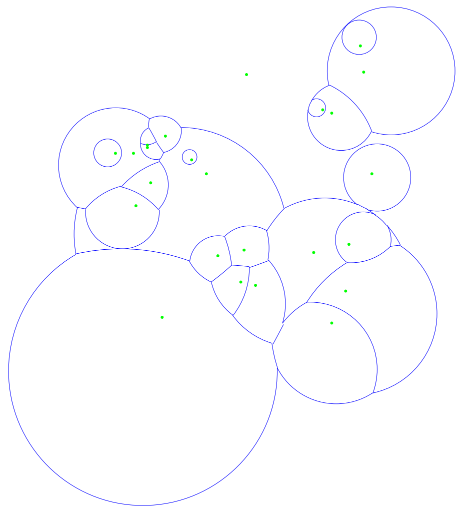

Figure 2. Möbius diagram in the plane

6.1.3. Structural complexity of the Delaunay triangulation

Participant: Jean-Daniel Boissonnat.

In collaboration with Dominique Attali (ENSIEG-LIS) and André Lieutier (Dassault Systèmes).

It is well known that the number of faces of the Delaunay triangulation of n points in $\mathbb{R}^3$, i.e. the number of its faces, can be as large as $\Omega(n^2)$.

The case of points distributed on a surface is of great practical importance in reverse engineering since most surface reconstruction algorithms first construct the Delaunay triangulation of a set of points measured on a surface. The time complexity of those methods therefore crucially depends on the complexity of the triangulation of points scattered over a surface in $\mathbb{R}^3$.

Several results have been obtained recently. In particular, Attali and Boissonnat proved last year a deterministic linear bound for the polyhedral case. In [30], we consider the case of points distributed on the boundary of a *smooth* surface. We prove that the complexity of the Delaunay triangulation of a (ε, κ)-sample of points scattered over a fixed *generic* surface is $O(n \log n)$. A surface is generic if, roughly, the ridges, i.e. the points on the surface where one of the principal curvature is locally maximal, is a finite set of curves. In particular, spheres and cylinders for which Erickson has exhibited an $\Omega(n\sqrt{n})$ lower bound are excluded.

6.2. Geometric computing and Cgal

6.2.1. Rounding of polygons

Participants: Olivier Devillers, Philippe Guigue.

One way to address robustness issues in geometric algorithms is to follow the exact computation paradigm that asks to evaluate all predicates exactly. Recent work has proved that this approach can be made very efficient for most single geometric algorithms. However, in some applications, it is necessary to embed the result in some representable space (say the grid of floating numbers) : we are then faced with the problem of rounding the result in accordance with the computed (possibly in an exact way) combinatorial output. This issue is especially critical when several algorithms are *cascaded*, i.e. when the output of an algorithm is used as input for another algorithm in a repeated way. For such use, one needs to round intermediate results while preserving some geometric properties. We have developed algorithms for boolean operations on polygons in the plane with guarantees on the inclusion between the true result and the rounded result and also guarantees on the distance and the number of vertices of the rounded result [12].

6.2.2. Visualization

Participants: Radu Ursu, Laurent Rineau.

CGAL now has a 2D visualization tool based on the Qt software from TrollTech. It has been chosen because of the portability feature (Windows/Unix). All 2D CGAL packages now have at least one demonstration program based on this tool.

6.2.3. Windows support

Participant: Radu Ursu.

Support for the Windows platform has been considerably improved in CGAL 3.0. In particular, the newest version of the Visual C++ compiler is supported. The user has now access to a standard installation tool Install Shield, and the use of the integrated development environment provided by Microsoft Developer Studio has been greatly facilitated.

6.3. Local geometric approximation

Key words: *Differential geometry*, *curvature tensor*.

6.3.1. Polynomial fitting of osculating jets

Participants: Frédéric Cazals, Marc Pouget.

Several applications from Computer Vision, Computer Graphics, Computer Aided Design or Computational Geometry require estimating local differential quantities from either a point cloud or a mesh sampled over a smooth curve or surface. In [51] is proposed an estimation method which consists of fitting the local representation of the manifold using a jet, and either use interpolation or approximation. A jet is a truncated Taylor expansion, and the incentive for using jets is that they encode all local geometric quantities — such as normal, curvatures, extrema of curvature.

On the way to using jets, the question of estimating differential properties is recasted into the more general framework of multivariate interpolation / approximation, a well-studied problem in numerical analysis. On a theoretical perspective, we prove several convergence results when the samples get denser. For curves and surfaces, these results involve asymptotic estimates with convergence rates depending upon the degree of the jet used. For the particular case of curves, an error bound is also derived. To the best of our knowledge, these results are among the first ones providing accurate estimates for differential quantities of order three and more. On the algorithmic side, we solve the interpolation/approximation problem using Vandermonde systems. Experimental results for surfaces of $\mathbb{R}^3$ are reported. These experiments illustrate the asymptotic convergence results, but also the robustness of the methods on general Computer Graphics models.

6.3.2. Approximation of the curvature measures and normal cycles

Participants: David Cohen-Steiner, Jean-Marie Morvan.

A first report [55] deals with the approximation of a smooth surface M by a triangulated mesh T. We give an explicit bound on the difference of the curvature measures of M and the curvature measures of T, when T is close to M. The result is obtained by applying the theory of the normal cycle.

In a second report [56], we give a general Riemannian framework to the study of approximation of curvature measures, using the theory of the normal cycle. Moreover, we introduce a differential form which allows to define a new type of curvature measure encoding the second fundamental form of a hypersurface, and to extend this notion to geometric compact subsets of a Riemannian manifold. Finally, if a geometric compact subset is close to a smooth hypersurface of a Riemannian manifold, we compare their second fundamental form (in the previous sense), and give a bound of their difference in terms of geometric invariants and the mass of the involved normal cycles.

6.4. Surface sampling, meshing and reconstruction

Key words: *Computational topology*, *surface mesh generation*, *implicit surfaces*, *point set surfaces*.

6.4.1. Isotopic meshing of implicit surfaces

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

In collaboration with Gert Vegter (University of Groningen).

Implicit equations are a popular way to encode geometric objects. Typical examples are CSG models, where objects are defined as results of boolean operations on simple geometric primitives. Given an implicit surface, associated geometric objects of interest, such as contour generators, are also defined by implicit equations. Another advantage of implicit representations is that they allow for efficient blending of surfaces, with obvious applications in CAD or metamorphosis. Finally, this type of representation is also relevant to other scientific fields, such as level sets methods or density estimation.

However, most graphical algorithms, and especially those implemented in hardware, cannot process implicit surfaces directly, and require that a piecewise linear approximation of the considered surface has been computed beforehand. As a consequence, polygonalization of implicit surfaces has been widely studied in the literature (e.g. the celebrated marching cube algorithm).

In [48], we give the first certified algorithm for isotopic polygonalization of smooth implicit surface. Assuming the critical points of the function defining the surface are known, the whole algorithm can be implemented in the setting of interval analysis. We only assume that the considered isosurface is smooth, i.e. it does not contain any critical point, which is generic by Sard's theorem. Our polygonalization is the zero-set of the linear interpolation of the implicit function on a mesh of $\mathbb{R}^3$. We first exhibit a set of conditions on the mesh used for interpolation that ensure the topological correctness. Then, we describe an algorithm for building a mesh satisfying these conditions, thereby leading to a provably correct polygonalization algorithm.

6.4.2. Quality-guaranteed surface sampling and meshing

Participants: Jean-Daniel Boissonnat, Steve Oudot.

The notion of ε-sample, as introduced by Amenta and Bern, has proven to be a key concept in the theory of sampled surfaces. Of particular interest is the fact that, if E is an ε-sample of a smooth surface S for a sufficiently small ε, then the Delaunay triangulation of E restricted to S, $\mathrm{Del}_{|S}(E)$, is a good approximation of S, both in a topological and in a geometric sense. Hence, if one can construct an ε-sample, one also gets a good approximation of the surface. Moreover, correct reconstruction is ensured by various algorithms.

We introduce the notion of loose ε-sample [49]. We show that the set of loose ε samples contains and is asymptotically identical to the set of ε-samples. The main advantage of loose ε-samples over ε-samples is that they are easier to check and to construct.

In [32], we present a construction algorithm which is a variant of Chew's surface meshing algorithm. Given a smooth closed surface S, the algorithm generates a sparse ε-sample E and at the same time a triangulated surface $\mathrm{Del}_{|S}(E)$. The triangulated surface has the same topological type as S, is close to S for the Hausdorff distance and has well-shaped facets. Moreover it can provide good approximations of normals, areas and curvatures. A remarkable feature of the algorithm is that the surface needs only to be known through an oracle that, given a line segment, detects whether the segment intersects the surface and, in the affirmative, returns an intersection point and the distance to the skeleton at that point. This makes the algorithm useful in a wide variety of contexts and for a large class of surfaces. Experimental results have shown that the method works remarkably well on various kinds of surfaces, including implicit algebraic (possibly non smooth) surfaces, polyhedral surfaces and point set surfaces.

With this new concept of point sample, we can build an algorithm that is able to mesh smooth closed surfaces with topological and geometric guarantees. Examples of algebraic surfaces meshed with the algorithm are illustrated in Figure 3. An example of a point set surface is shown in Figure 4.

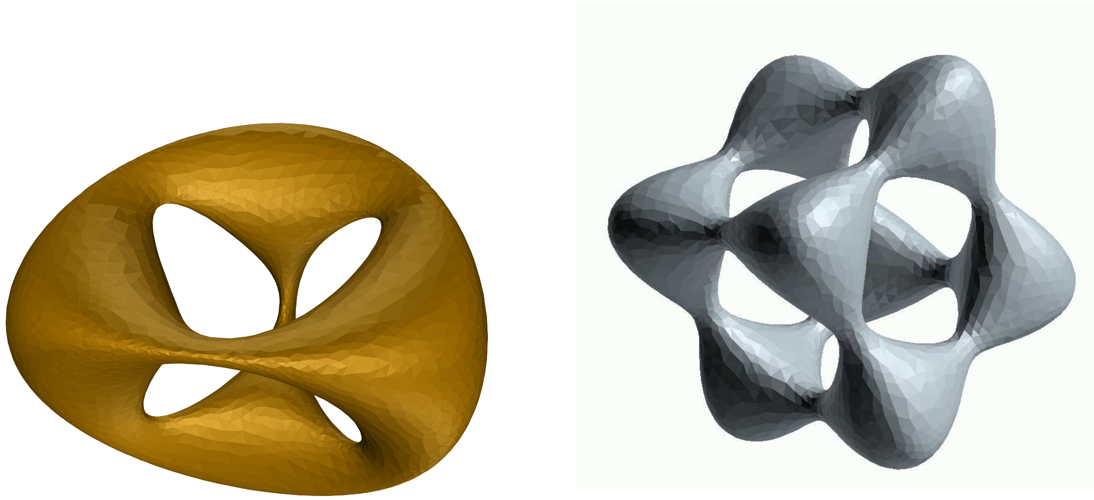

Figure 3. Examples of quality-guaranteed meshes of algebraic surfaces

6.4.3. A geometric-based convection approach to 3-D reconstruction

Participant: Raphaelle Chaine.

Surface reconstruction algorithms produce piece-wise linear approximations of a surface S from a finite, sufficiently dense, subset of its points. In [52][37], we present a fast algorithm for surface reconstruction from scattered data sets. This algorithm is inspired of an existing numerical convection scheme developed by Zhao, Osher and Fedkiw. Unlike this latter, the result of our algorithm does not depend on the precision of a (rectangular) grid. The reconstructed surface is simply a set of oriented faces located into the 3D Delaunay triangulation of the points. It is the result of the evolution of an oriented pseudo-surface. The representation of the evolving pseudo-surface uses an appropriate data structure together with operations that allow deformation and topological changes of it. The presented algorithm can handle complicated topologies and, unlike most of the others schemes, it involves no heuristic. The complexity of that method is that of the 3D Delaunay triangulation of the points. We present results of this algorithm which turned out to be efficient even in presence of noise.

6.5. Parametrization and remeshing of polyhedral surfaces

Key words: *surface remeshing*, *isotropic sampling*, *centroidal Voronoi diagrams*, *anisotropic sampling*, *polygon meshes*, *lines of curvatures*, *tensor fields*.

6.5.1. Isotropic surface remeshing

Participants: Pierre Alliez, Olivier Devillers.

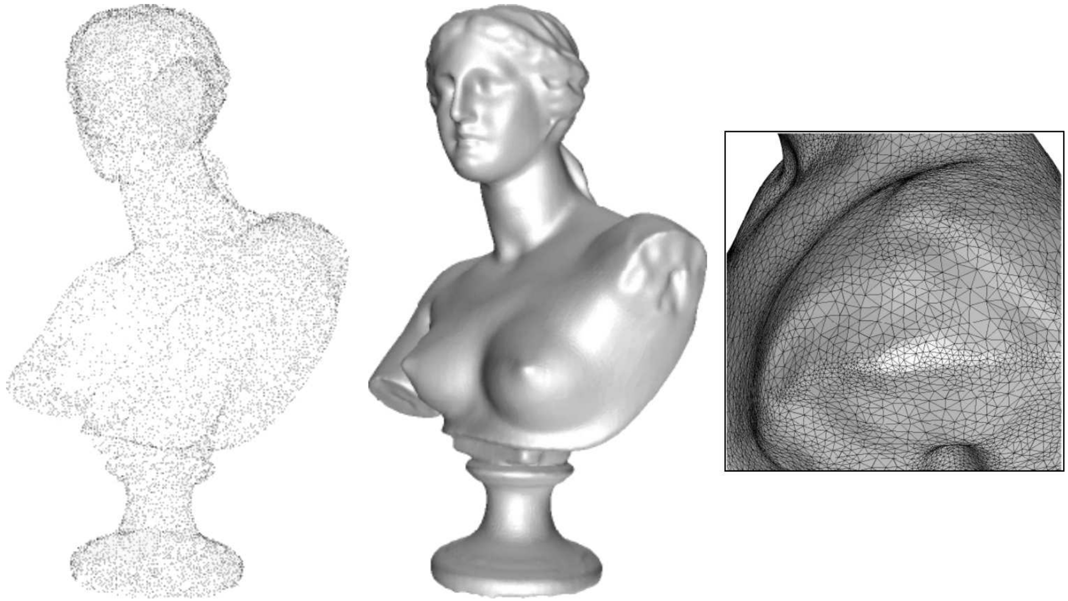

Figure 4. A point set surface and the corresponding mesh

In collaboration with M. Isenburg (University of North Carolina at Chapell Hill) and É. Colin de Verdière (École Normale Supérieure, Paris).

In [28], we propose a new method for isotropic remeshing of triangulated surface meshes. Given a triangulated surface mesh to be resampled and a user-specified density function defined over it, we first distribute the desired number of samples by generalizing error diffusion, commonly used in image halftoning, to work directly on mesh triangles and feature edges. We then use the resulting sampling as an initial configuration for building a weighted centroidal Voronoi tessellation in a conformal parameter space, where the specified density function is used for weighting. We finally create the mesh by lifting the corresponding constrained Delaunay triangulation from parameter space. A precise control over the sampling is obtained through a flexible design of the density function, the latter being possibly low-pass filtered to obtain a smoother gradation (see Fig.5)). We demonstrate the versatility of our approach through various remeshing examples.

6.5.2. Anisotropic polygonal remeshing

Participants: Pierre Alliez, David Cohen-Steiner, Olivier Devillers.

In collaboration with B. Lévy (Loria, Nancy) and M. Desbrun (University of Southern California).

In [13][46], we propose a novel polygonal remeshing technique that exploits a key aspect of surfaces: the intrinsic anisotropy of natural or man-made geometry. In particular, we use curvature directions to drive the remeshing process, mimicking the lines that artists themselves would use when creating 3D models from scratch. After extracting and smoothing the curvature tensor field of an input genus-0 surface patch, lines of minimum and maximum curvatures are used to determine appropriate edges for the remeshed version in anisotropic regions, while spherical regions are simply point-sampled since there is no natural direction of symmetry locally. As a result our technique generates polygon meshes mainly composed of quads in anisotropic regions, and of triangles in spherical regions (See Fig. 6). Our approach provides the flexibility to produce meshes ranging from isotropic to anisotropic, from coarse to dense, and from uniform to curvature adapted.

6.5.3. Isotropic remeshing of surfaces: a local parameterization approach

Participant: Pierre Alliez.

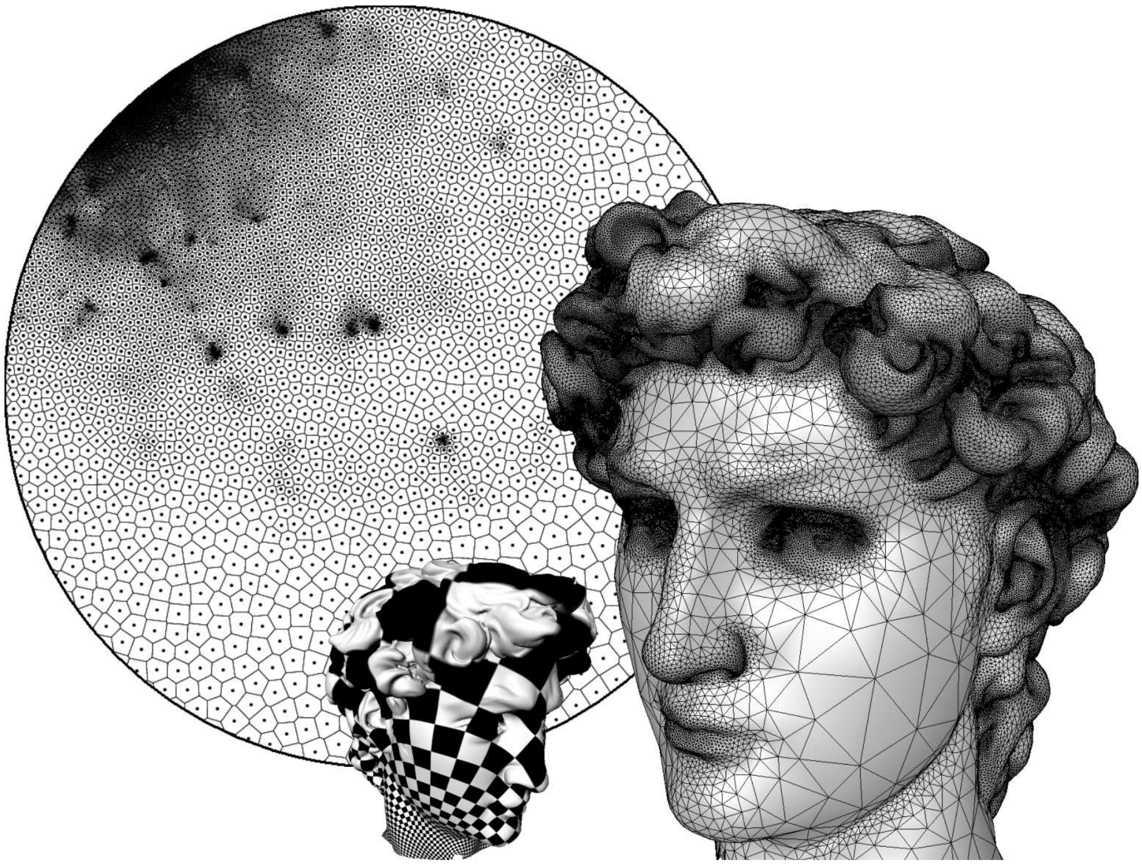

Figure 5. Curvature-adapted remeshing of the Digital Michelangelo David head model.

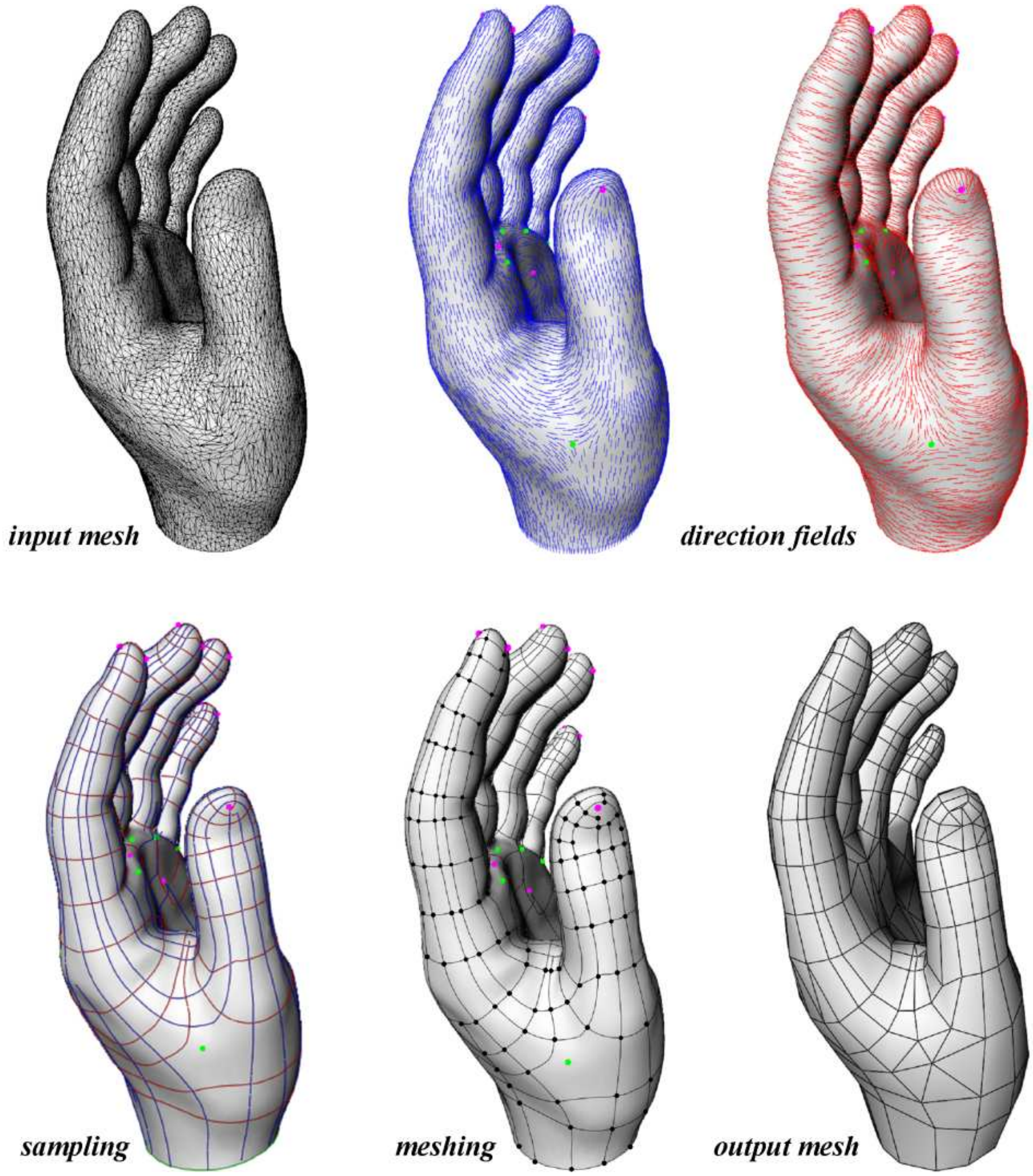

Figure 6. From an input triangulated geometry, the curvature tensor field is estimated, then smoothed, and its umbilics are deduced (colored dots). Lines of curvatures (following the principal directions) are then traced on the surface, with a local density guided by the principal curvatures, while usual point-sampling is used near umbilic points (spherical regions). The final mesh is finally extracted by subsampling, and conforming-edge insertion. The result is an anisotropic mesh, with elongated quads aligned to the original principal directions, and triangles in isotropic regions. Such an anisotropy-based placement of the edges and cells makes for a very efficient and high-quality description of the geometry.

In collaboration with V. Surazhsky and C. Gotsman (Technion, Haifa, Israel).
We present a method for isotropic remeshing of arbitrary genus surfaces [44]. The method is based on a mesh adaptation process, namely, a sequence of local modifications performed on a copy of the original mesh, while referring to the original mesh geometry. The algorithm has three stages. In the first stage, the required number of vertices is generated by iterative simplification or refinement. The second stage performs an initial vertex partition using an area-based relaxation method. The third stage achieves precise isotropic vertex sampling prescribed by a given density function on the mesh. We use a modification of Lloyd's relaxation method to construct a weighted centroidal Voronoi tessellation of the mesh. We apply these iterations locally on small patches of the mesh that are parameterized into the 2D plane. This allows us to handle arbitrary complex meshes with any genus and any number of boundaries. The efficiency and the accuracy of the remeshing process is achieved using a patchwise parameterization technique.

6.5.4. Discrete Morse-Smale decompositions with applications to docking

Participants: Frédéric Cazals, Thomas Lewiner.

In collaboration with F. Chazal, Mathematics Department, Université de Bourgogne, France.
Docking is the process by which two or several molecules form a complex. Docking involves the geometry of the molecular surfaces, as well as chemical and energetical considerations. In the mid-eighties, Connolly proposed a docking algorithm matching surface *knobs* with surface *depressions*. Knobs and depressions refer to the extrema of the *Connolly* function, which is defined as follows. Given a surface $\mathcal{M}$ bounding a three-dimensional domain X, and a sphere S centered at a point p of $\mathcal{M}$, the Connolly function is equal to the solid angle of the portion of S contained within X.

We recast the notions of knob and depression of the Connolly function in the framework of Morse theory for functions defined over two-dimensional manifolds [50]. First, we study the critical points of the Connolly function for smooth surfaces. Second, we provide an efficient algorithm for computing the Connolly function over a triangulated surface. Third, we introduce a Morse-Smale decomposition based on Forman's discrete Morse theory, and provide an $O(n \log n)$ algorithm to construct it where n is the number of faces of the surface. This decomposition induces a partition of the surface into regions of homogeneous flow, and provides an elegant way to relate local quantities to global ones —from critical points to Euler's characteristic of the surface. Fourth, we apply this Morse-Smale decomposition to the discrete gradient vector field induced by Connolly's function, and present experimental results for several mesh models.

6.6. Geometry compression

Key words: *surface mesh coding*, *shape compression*, *volume mesh coding*.

6.6.1. Compressing hexahedral volume meshes

Participant: Pierre Alliez.

In collaboration with M. Isenburg, University of North Carolina at Chapell Hill.
Unstructured hexahedral volume meshes are of particular interest for visualization and simulation applications. They allow regular tiling of the three-dimensional space and show good numerical behavior in finite element computations. Beside such appealing properties, volume meshes take huge amount of space when stored in a raw format. In this paper we present a technique for encoding connectivity and geometry of unstructured hexahedral volume meshes [26]. For connectivity compression, we extend the idea of coding with degrees as pioneered by Touma and Gotsman to volume meshes. Hexahedral connectivity is coded as a sequence of edge degrees. This naturally exploits the regularity of typical hexahedral meshes. We achieve compression rates of around 1.5 bits per hexahedron (bph) that go down to 0.18 bph for regular meshes. On our test meshes the average connectivity compression ratio is $1 : 162.7$. For geometry compression, we perform simple parallelogram prediction on uniformly quantized vertices within the side of a hexahedron. Tests show an average geometry compression ratio of $1 : 3.7$ at a quantization level of 16 bits.

6.6.2. Mesh compression, a survey

Participants: Pierre Alliez, Olivier Devillers.

In collaboration with M. Isenburg (University of North Carolina at Chapell Hill) and S. Valette (INSA Lyon).
The fast development of the Internet allows transmission of geometric models. Among various representations, meshes provide effective means to model complex shapes. Since they often require a huge amount of data for storage and/or transmission in a raw data format, many algorithms have been proposed to compress them efficiently. In a survey paper [29], we examine mesh compression technologies developed for single-rate and progressive compression of surface and volume meshes.

6.6.3. Progressive transmission of triangulated models over the net

Participant: Olivier Devillers.

In collaboration with P.-M. Gandoin and M. Trentini (École Polytechnique and ENST).
Based on previous work described in Pierre-Marie Gandoin thesis, we have experimented a compression scheme for an application visualizing several objects with transmission of data on the internet [45]. The different objects in the scene are transmitted and decompressed simultaneously. Since the different objects are competing for the bandwith, the priority between the different objects is fixed by the client and driven by the proximity of the object from the view point.

6.6.4. Recent advances in compression of 3D meshes

Participant: Pierre Alliez.

In collaboration with C. Gotsman (Technion, Haifa, Israel).
3D meshes are widely used in graphic and simulation applications for approximating 3D objects. When representing complex shapes in a raw data format, meshes consume a large amount of space. Applications calling for compact storage and fast transmission of 3D meshes have motivated the multitude of algorithms developed to efficiently compress these datasets. In this paper we survey recent developments in compression of 3D surface meshes. We survey the main ideas and intuition behind techniques for single-rate and progressive mesh coding. Where possible, we discuss the theoretical results obtained on the asymptotic behavior and the optimality of the approach. We also list some open questions and directions of future research [47].

6.6.5. Compressing polygonal data with hardware constraints

Participants: Pierre Alliez, Olivier Devillers, Mathieu Monnier.

In this work, we are designing a compression algorithm dedicated to polygons, and with extremely fast decompression speed and low memory requirement, since the targeted application has to run on low speed processor such as PDA.

We have experimented with several compression schemes and compared them together. The best result has been obtained with the combination of various techniques depending on the context (mainly the polygon size). For the basic level of compression, we succeed to reach almost the same compression rate as arithmetic coding but without its expensive cost using a collection of Huffman's trees [61].

7. Contracts and Grants with Industry

7.1. Geometry Factory

Participant: Radu Ursu.

The CGAL library is developed by a European consortium. In order to achieve the transfer and diffusion of CGAL, a start-up called Geometry Factory has been founded in January 2003 by Andreas Fabri (http://www.GeometryFactory.com). Geometry Factory has the support of the consortium.

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 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...

First customers are from various application areas : geophysical modelling (IFP, Midland Valley Exploration), geographic information systems (Leica Geosystems), location based services (TruePosition), image processing (Toshiba, BAE), digital maps (Durch Topographic Service).

During the creation process, we realized in particular that it was very important to offer better support in CGAL for the Windows/Visual C++ platform. Radu Ursu got an ODL position to work on these aspects. He now works part time for Geometry Factory.

7.2. Benomad

Participants: Pierre Alliez, Olivier Devillers, Mathieu Monnier.

Benomad is a start-up devoted to software for geometric data, and in particular geographic data on PDA (http://www.benomad.com).

One of the goals of Benomad was to have the software running on PDAs. For processors with such a low computational power, state of the art compression algorithms, e.g. arithmetic coding, were too expensive. We have developed a geometric coder inspired by standard geometric coding techniques to reduce the problem to a word coding problem. Then by a careful use of Huffman coding, we almost reach the compression ratio of the best algorithms which are much more computationally demanding.

8. Other Grants and Activities

8.1. National initiatives

8.1.1. INRIA New Investigation Grant Protein-Protein Docking

Participants: Jean-Daniel Boissonnat, Frédéric Cazals, Thomas Lewiner.

Also involved: Xavier Cavin and Nicolas Rey (ISA project, LORIA), Bernard Maigret and Christophe Chipot (CNRS Nancy).

Given a cell receptor involved in a given disease, Virtual Screening (VS) is the computational process aiming at selecting good drug candidates for that receptor. As opposed to High Throuput Screening which consists of performing wet chemistry experiments to qualify potential drugs, VS has the advantage of being cheaper and faster (more candidate molecules tested). Unfortunately, the effectiveness of VS depends upon the quality of the score functions used, and a VS process usually involves three filters —coarse, medium, fine, each being more accurate and more time consuming than its predecessor.

The *Protein-Protein Docking* ARC aims at contributing to the state-of-the-art VS methods. The focus is on improving coarse filters using more efficient molecular representations [50], together with haptic rendering.

8.1.2. INRIA New Investigation Grant telegeo

Participants: Pierre Alliez, Frédéric Cazals, David Cohen-Steiner, Olivier Devillers, Mathieu Monnier, Marc Pouget, Mario Trentini.

ARC TELEGEO *(Geometry and Telecommunications) :*
http://www-sop.inria.fr/prisme/telegeo/

The objective of TELEGEO is a two-years coordinated research effort, carried out by a total of 26 people at INRIA Sophia-Antipolis, LORIA Nancy, IRISA Rennes, ENST Paris and INSA Lyon, aimed at facilitating geometry processing and compression for applications to heterogeneous networks. Accomplishments of the action include (i) a prototypical client-server software for progressive transmission of triangle meshes [45], (ii) a benchmark coder for polygon mesh compression. An online Web implementation and a downloadable standalone version of the pure Java polygon mesh compressor are available online at http://www.cs.unc.edu/~isenburg/research/pmc/. This software is meant to provide benchmark bit-rates for future research in the area of mesh compression. It compresses not only the connectivity and geometry of a polygon mesh, but also one optional layer of texture coordinates, (iii) a new technique for compressing hexahedral volume meshes (published at Pacific Graphics in 2002), (iv) a new technique for anisotropic surface remeshing (published at Siggraph [13]), and (v) a new technique for watermarking of 3D triangle mesh geometry.

8.1.3. Visiting scientists

The GEOMETRICA *seminar : http://www-sop.inria.fr/prisme/seminaire/*

The GEOMETRICA seminar featured presentations from the following visiting scientists:
– Christian Mercat, Technical University of Berlin
– Jean-Jacques Risler, Institut de Mathématiques, Paris 6
– Frédéric Chazal, Université de Bourgogne
– Boris Thibert, Institut Girard Desargues, Lyon
– Mark Moll, Rice University, USA
– François Cayre, ENST Paris
– Mahmoud Melkemi, Université Claude Bernard, Lyon
– Anders Adamson, Technische Universität Darmstadt

8.2. European initiatives

8.2.1. ecg

INRIA is the coordinating site of this project. J-D. Boissonnat is the project leader and M. Teillaud (GALAAD) the technical coordinator.
– Acronym : ECG, numéro IST-2000-26473
– Title : Effective Computational Geometry for Curves and Surfaces.
– Specific program : IST
– RTD (FET Open)
– Starting date : may 1st, 2001 - Duration : 3 years
– Participation mode of Inria : Coordinator
– Other participants : ETH (Zürich), Freie Universität (Berlin), Rijksuniversiteit (Groningen), Max Plank Institute (Sarrebruck), Tel Aviv University.
– Abstract : Effective processing of curved objects in computational geometry. Geometric algorithms for curves and surfaces, algebraic issues, robustness issues, geometric approximation.

The web site of the project includes a detailled description of the objectives and all results http://www-sop.inria.fr/prisme/ECG/.

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 *Theoretical Computer Science*, *Algorithmica*, *International Journal of Computational Geometry and Applications*, *Computational Geometry : Theory and Applications*, and *The Visual Computer*
- He also co-edited the book *Algorithmic Foundations of Robotics V*, Springer 2003.
- M. Yvinec is a member of the editorial board of *Journal of Discrete Algorithms*.
- S. Pion is co-editor of a special issue of *Computational Geometry : Theory and Applications* on robustness issues.
- S. Pion and M. Yvinec are members of the CGAL editorial board.

9.1.2. Conference programs committees

- Jean-Daniel Boissonnat was on the program committee of ESA 2003 (European Symposium on Algorithms) held in Budapest, September 2003.
- Jean-Daniel Boissonnat and Frédéric Cazals were members of the program committee of the Symposium on Geometry Processing, held in Aachen, June 2003.
- Olivier Devillers was a member of the program committee of the ACM Symposium on Computational Geometry, held in San Diego, June 2003.

9.1.3. Conferences organization

- Mariette Yvinec organized the workshop Journées de Geométrie Algorithmique, JGA03, in Giens, 14-19 september 2003.
- Olivier Devillers and Pierre Alliez organized the Workshop for Geometry Compression in Sophia-Antipolis in november 2003.

9.1.4. PhD thesis and HDR committees

- Jean-Daniel Boissonnat was a member of the PhD thesis committees of Franck Hetroy (INPG), Nicolas Ray (université de Nancy 2), Boris Thibert (université Claude Bernard).
- Jean-Daniel Boissonnat was a member of the habilitation committee of M. Melkemi (université Claude Bernard).
- Frédéric Cazals was a member of the PhD thesis committee of Cédric Chappuis, University of Compiègne, France. Thesis title: *Optimisation inverse de maillages surfaciques de pièces mécaniques par interpolation diffuse*.
- Mariette Yvinec was a member of the PhD thesis committee of Francois Lepage, University of Nancy. Thesis title: *Génération de maillages tridimensionnels pour la simulation des phénomènes physiques en géosciences*.
- Mariette Yvinec was a member of the PhD thesis committee of David Ledez, University of Nancy. Thesis title: *Modélisation d'objets naturels par formulation implicite*.

9.1.5. Other committees

Jean-Daniel Boissonnat is
- chairman of the Comité des Projets of INRIA Sophia-Antipolis.
- member of the Commission d'Evaluation of INRIA.
- member of the scientific committee of ENS-Lyon.
- member of the AFIT advisory board (Association Française d'Informatique Théorique).
- Jean-Daniel Boissonnat was a member of the selection committee of INRIA Lorraine and INRIA Sophia-Antipolis.
- Frédéric Cazals is member of the « Commission de spécialistes » of the Mathematics Department of the University of Bourgogne, Dijon, France.
- Olivier Devillers is chairman of the « Comité des utilisateurs des moyens informatiques de l'INRIA Sophia-Antipolis » (CUMI).
- Olivier Devillers is member of the committee for « détachements » at INRIA Sophia-Antipolis.
- Sylvain Pion is a member of the « Commission du Développement Logiciel » (CDL) at INRIA Sophia-Antipolis.

9.1.6. WWW server

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

The GEOMETRICA project maintains on its web site a collection of comprehensive sheets about the subjects presented in this report, as well as downloadable software.

A surface reconstruction service is also available (see section 5.2).

9.2. Teaching

9.2.1. Teaching at universities

- J-D. Boissonnat co-chairs with D. Lazard (Paris 6) the option « Géométrie et Calcul Formel » of the DEA d'algorithmique de Paris.
- Olivier Devillers is chairman of the DEA : « Images and vision » at Nice Sophia-Antipolis University.
- Olivier Devillers is professor « Chargé de cours » at École Polytechnique.

- DEA Algorithmique, Paris, (2003-2004), Cours de tronc commun : Géométrie Algorithmique (24h) (J.-D. Boissonnat)
- DEA Algorithmique, Paris, Filière Géométrie et Calcul Formel, Triangulations, maillages et modélisation géométrique, 20h, (J-D. Boissonnat et M. Yvinec)
- DEA Imagerie Vision Robotique (Grenoble), Introduction to Differential Geometry, 6h (F. Cazals)
- Ecole Centrale Paris, Computational Geometry and Molecular Modeling, 7h, (F. Cazals)
- École Polytechnique (Palaiseau), Computational Geometry and Image Synthesis, 30h (O. Devillers).
- École Polytechnique (Palaiseau), Basis of computer science, 60h (O. Devillers).
- ISIA (Sophia-Antipolis), Computational Geometry, 10h (O. Devillers).
- ESSI (Sophia-Antipolis), Computational Geometry, 10h (O. Devillers).
- Maîtrise Informatique (Nice), Computational Geometry, 16h (O. Devillers, J. Flötotto).
- DEA Images et Vision (Sophia-Antipolis), From Computational Geometry to Geometric Computing, 15h (O. Devillers).

9.2.2. Internships

Internship proposals can be seen on the web at http://www-sop.inria.fr/prisme/Stages/
- Christophe Delage, *Möbius diagrams in the plane*, Stage de DEA, ENS-Lyon
- Mathieu Monnier, *Compressing vectorial data*, Third year internship at École Polytechnique.
- Marie Samozino, *Largeur locale* Stage de DEA Images Vision, Université de Nice

9.2.3. Ongoing Ph.D. theses

- Luca Castelli, *Compression et entropie d'objets pour la synthèse d'images* en cotutelle avec l'École Polytechnique.
- David Cohen-Steiner, *Echantillonnage de surfaces*, École Polytechnique.
- Christophe Delage, *Non affine Voronoi diagrams*, ENS-Lyon.
- Thomas Lewiner, *Computational Topology and Applications in Molecular Modeling*, École Polytechnique.
- Steve Oudot, *Maillages de surfaces*, École Polytechnique.
- Marc Pouget, *Computational Differential Geometry*, université de Nice-Sophia Antipolis.
- Laurent Rineau, *Maillages tétraédriques*, Université de Paris VI.
- Marie Samozino, *Filtrage, simplification et représentation multirésolution d'objets géométriques reconstruits*, Université de Nice-Sophia Antipolis.

9.2.4. Ph.D. defenses

- Julia Flötotto, *A coordinate system associated to a point cloud issued from a manifold: definition, properties and applications*, University of Nice-Sophia Antipolis [11].
- Philippe Guigue, *Constructions géométriques à précision fixée*, Université de Nice-Sophia Antipolis [12].

9.3. Participation to conferences, seminars, invitations

9.3.1. Scientific visits

P. Alliez visited C. Gotsman at the TECHNION in March-April 2003 concerning joint work on compression, parameterization, and remeshing.

S. Pion visited I. Z. Emiris at the University of Athens in November 2003 concerning work on algebraic and implementation issues for geometric predicates on curved objects (collaboration with GALAAD).

9.3.2. Talks in conferences and seminars

Members of the project presented articles at conferences. The reader can refer to the bibliography to obtain the corresponding list.

Moreover, they made presentations during the following events :
- Invited talk at Journées Nationales de Calcul Formel, Quelques résultats récents sur le calcul des diagrammes de Voronoï, (J-D. Boissonnat).
- ALEA'03, January 2003, CIRM, Randomized jumplists: a jump-and-walk dictionary data-structure, (F. Cazals).
- DIMACS Workshop on Surface Reconstruction, May 2003, DIMACS, Point clouds, Surface Reconstruction, and Differential Geometry: two selected topics, (F. Cazals).
- « Journées de géométrie algorithmique », Sep 2003, Giens France
Compression de modèles géométriques (Olivier Devillers and Pierre Alliez)
Approximation de surfaces - deuxième étape : à propos des r-échantillons (Steve Oudot)
Estimation des Quantités Différentielles par Ajustement Polynomial des Jets Osculateurs (Marc Pouget)
Sur une Analyse des Formes Moléculaires basée sur le Complexe de Morse-Smale et la Fonction de Connolly (Frédéric Cazals)
- GMDG (Geometric Modeling and Differential Geometry), Sep 2003, Erbach, Germany. *Remeshing of surfaces* (P. Alliez).
- ECG Workshop on Applications involving geometric algorithms with curved objects, Sep 2003, Saarbruecken, Germany. *Isotropic Remeshing of Surfaces* (P. Alliez).
- Workshop on geometry compression, November 2003, Anisotropic Polygonal Remeshing (P. Alliez); Canonical triangulation of a graph, with coding application (L. Castelli).
- SIAM Conference on Geometric Design and Computing, Seattle, November 2003, Sampling, meshing and interactive surface reconstruction (J-D. Boissonnat). Invited talk of the minisymposium on point set surfaces.

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