RESEARCH CENTRE

Nancy - Grand Est

IN PARTNERSHIP WITH:

CNRS, Université de Lorraine

2020
ACTIVITY REPORT

Project-Team
PIXEL

Structure geometrical shapes

IN COLLABORATION WITH: Laboratoire lorrain de recherche en informatique et ses applications (LORIA)

DOMAIN

Perception, Cognition and Interaction

THEME

Interaction and visualization

Contents

Project-Team PIXEL

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Keywords

Computer sciences and digital sciences

- A5.5.1. – Geometrical modeling
- A5.5.2. – Rendering
- A6.2.8. – Computational geometry and meshes
- A8.1. – Discrete mathematics, combinatorics
- A8.3. – Geometry, Topology

Other research topics and application domains

- B3.3.1. – Earth and subsoil
- B5.1. – Factory of the future
- B5.7. – 3D printing
- B9.2.2. – Cinema, Television
- B9.2.3. – Video games

1 Team members, visitors, external collaborators

Research Scientists

- Laurent Alonso [Inria, Researcher, from Mar 2020]
- Etienne Corman [CNRS, Researcher, from Mar 2020]
- Nicolas Ray [Inria, Researcher, from Mar 2020]

Faculty Members

- Dmitry Sokolov [Team leader, Univ de Lorraine, Associate Professor, from Mar 2020, HDR]
- Dobrina Boltcheva [Univ de Lorraine, Associate Professor]

Post-Doctoral Fellow

- Sebastian Von Hausegger [Inria, from Mar 2020 until Sep 2020]

PhD Students

- Justine Basselin [Rhino Terrain, CIFRE]
- Guillaume Coiffier [Univ de Lorraine, from Sep 2020]
- David Desobry [Inria, from Oct 2020]
- Francois Protais [Inria, from Mar 2020]

Technical Staff

- David Lopez [Univ de Lorraine, Engineer, from Nov 2020]

Interns and Apprentices

- Samy Benhoussa [Univ de Lorraine, from Apr 2020 until Jun 2020]
- Leila Bentayeb [Inria, from Jun 2020 until Aug 2020]
- Victor Blanchi [Univ de Lorraine, from Jun 2020 until Aug 2020]
- Yoann Coudert-Osmont [Univ de Lorraine, from Apr 2020 until Aug 2020]
- David Desobry [Inria, from Mar 2020 until Aug 2020]
- Aude Marêché [Inria, from Apr 2020 until May 2020]

Administrative Assistants

- Celine Cordier [Inria, from Mar 2020]
- Virginie Priester [CNRS]

External Collaborator

- Herve Barthelemy [Rhino Terrain, from Mar 2020]

2 Overall objectives

PIXEL is a research team stemming from team ALICE founded in 2004 by Bruno Lévy. The main scientific goal of ALICE was to develop new algorithms for computer graphics, with a special focus on geometry processing. From 2004 to 2006, we developed new methods for automatic texture mapping (LSCM, ABF++, PGP), that became the de-facto standards. Then we realized that these algorithms could be used to create an abstraction of shapes, that could be used for geometry processing and modeling purposes, which we developed from 2007 to 2013 within the GOODSHAPE StG ERC project. We transformed the research prototype stemming from this project into an industrial geometry processing software, with the VORPALINE PoC ERC project, and commercialized it (TOTAL, Dassault Systems, + GeonX and ANSYS currently under discussion). From 2013 to 2018, we developed more contacts and cooperations with the "scientific computing" and "meshing" research communities.

After a part of the team "spun off" around Sylvain Lefebvre and his ERC project SHAPEFORGE to become the MFX team (on additive manufacturing and computer graphics), we progressively moved the center of gravity of the rest of the team from computer graphics towards scientific computing and computational physics, in terms of cooperations, publications and industrial transfer.

We realized that *geometry* plays a central role in numerical simulation, and that "cross-pollinization" with methods from our field (graphics) will lead to original algorithms. In particular, computer graphics routinely uses irregular and dynamic data structures, more seldom encountered in scientific computing. Conversely, scientific computing routinely uses mathematical tools that are not well spread and not well understood in computer graphics. Our goal is to establish a stronger connection between both domains, and exploit the fundamental aspects of both scientific cultures to develop new algorithms for computational physics.

2.1 Scientific grounds

Mesh generation is a notoriously difficult task. A quick search on the NSF grant web page [1] with "mesh generation AND finite element" keywords returns more than 30 currently active grants for a total of $8 million. **NASA indicates mesh generation as one of the major challenges for 2030 [49], and estimates that it costs 80% of time and effort in numerical simulation.** This is due to the need for constructing supports that match both the geometry and the physics of the system to be modeled. In our team we pay a particular attention to scientific computing, because we believe it has a world changing impact.

It is very unsatisfactory that meshing, i.e. just "preparing the data" for the simulation, eats up the major part of the time and effort. Our goal is to make the situation evolve, by studying the influence of shapes and discretizations, and inventing new algorithms to automatically generate meshes that can be directly used in scientific computing. This goal is a result of our progressive shift from pure graphics ("Geometry and Lighting") to real world problems ("Shape Fidelity").

Meshing is so central in geometric modeling because it provides a way to represent functions on the objects studied (texture coordinates, temperature, pressure, speed, etc.). There are numerous ways to represent functions, but if we suppose that the functions are piecewise smooth, the most versatile way is to discretize the domain of interest. Ways to discretize a domain range from point clouds to hexahedral meshes; let us list a few of them sorted by the amount of structure each representation has to offer (refer to Figure 1).

- At one end of the spectrum there are **point clouds:** they exhibit no structure at all (white noise point samples) or very little (blue noise point samples). Recent explosive development of acquisition techniques (e.g. scanning or photogrammetry) provides an easy way to build 3D models of real-world objects that range from figurines and cultural heritage objects to geological outcrops and entire city scans. These technologies produce massive, unstructured data (billions of 3D points per scene) that can be directly used for visualization purposes, but this data is not suitable for high-level geometry processing algorithms and numerical simulations that usually expect meshes. Therefore, at the very beginning of the acquisition-modeling-simulation-analysis pipeline, powerful scan-to-mesh algorithms are required.

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[1] `https://www.nsf.gov/awardsearch`

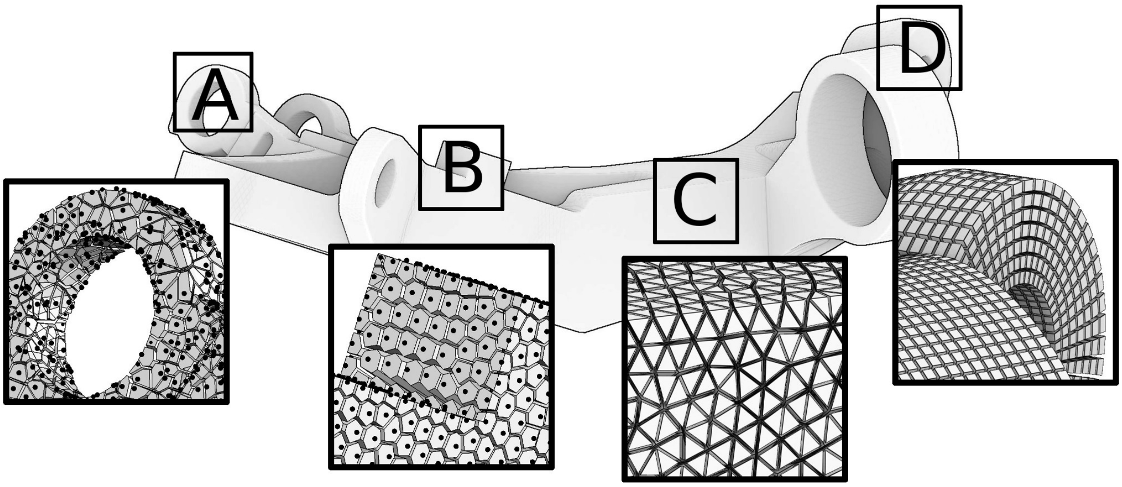

Figure 1: There is a wide range of possibilities to discretize a given domain. **(A)** Completely unstructured, white noise point sampling; **(B)** Blue noise point sampling exhibits some structure; **(C)** tetrahedral mesh; **(D)** hexahedral mesh.

During the last decade, many solutions have already been proposed [45, 28, 39, 40, 34], but the problem of building a good mesh from scattered 3D points is far from being solved. Beside the fact that the data is unusually large, the existing algorithms are challenged also by the extreme variation of data quality. Raw point clouds have many defects, they are often corrupted with noise, redundant, incomplete (due to occlusions): *they all are uncertain.*

- **Triangulated surfaces** are ubiquitous, they are the most widely used representation for 3D objects. Some applications like 3D printing do not impose heavy requirements on the surface: typically it has to be watertight, but triangles can have an arbitrary shape. Other applications like texturing require very regular meshes, because they suffer from elongated triangles with large angles.

  While being a common solution for many problems, triangle mesh generation is still an active topic of research. The diversity of representations (meshes, NURBS, ...) and file formats often results in a "Babel" problem when one has to exchange data. The only common representation is often the mesh used for visualization, that has in most cases many defects, such as overlaps, gaps or skinny triangles. Re-injecting this solution into the modeling-analysis loop is non-trivial, since again this representation is not well adapted to analysis.

- **Tetrahedral meshes** are the volumic equivalent of triangle meshes, they are very common in the scientific computing community. Tetrahedral meshing is now a mature technology. It is remarkable that still today all the existing software used in the industry is built on top of a handful of kernels, all written by a small number of individuals [32, 47, 53, 35, 46, 48, 33, 27].

  Meshing requires a long-term, focused, dedicated research effort, that combines deep theoretical studies with advanced software development. We have the ambition bring to this kind of maturity a different type of mesh (structured, with hexahedra), which is highly desirable for some simulations, and for which, unlike tetrahedra, no satisfying automatic solution exists. In the light of recent contributions, we believe that the domain is ready to overcome the principal difficulties.

- Finally, at the most structured end of the spectrum there are **hexahedral meshes** composed of deformed cubes (hexahedra). They are preferred for certain physics simulations (deformation mechanics, fluid dynamics ...) because they can significantly improve both speed and accuracy. This is because (1) they contain a smaller number of elements (5-6 tetrahedra for a single hexahedron), (2) the associated tri-linear function basis has cubic terms that can better capture higher order variations, (3) they avoid the locking phenomena encountered with tetrahedra [25], (4) hexahedral meshes exploit inherent tensor product structure and (5) hexahedral meshes are superior in direction dominated physical simulations (boundary layer, shock waves, etc). Being extremely regular, hexahedral meshes are often claimed to be The Holy Grail for many finite element methods [26], outperforming tetrahedral meshes both in terms of computational speed and accuracy.

Despite 30 years of research efforts and important advances, mainly by the Lawrence Livermore National Labs in the U.S. [52, 51], hexahedral meshing still requires considerable manual intervention in most cases (days, weeks and even months for the most complicated domains). Some automatic methods exist [38, 55], that constrain the boundary into a regular grid, but they are not fully satisfactory either, since the grid is not aligned with the boundary. The advancing front method [24] does not have this problem, but generates irregular elements on the medial axis, where the fronts collide. Thus, *there is no fully automatic algorithm that results in satisfactory boundary alignment.*

3 Research program

3.1 Point clouds

Currently, transforming the raw point cloud into a triangular mesh is a long pipeline involving disparate geometry processing algorithms:

- *Point pre-processing:* colorization, filtering to remove unwanted background, first noise reduction along acquisition viewpoint;
- *Registration:* cloud-to-cloud alignment, filtering of remaining noise, registration refinement;
- *Mesh generation:* triangular mesh from the complete point cloud, re-meshing, smoothing.

The output of this pipeline is a locally structured model which is used in downstream mesh analysis methods such as feature extraction, segmentation in meaningful parts or building CAD models.

It is well known that point cloud data contains measurement errors due to factors related to the external environment and to the measurement system itself [50, 44, 29]. These errors propagate through all processing steps: pre-processing, registration and mesh generation. Even worse, the heterogeneous nature of different processing steps makes it extremely difficult to know *how* these errors propagate through the pipeline. To give an example, for cloud-to-cloud alignment it is necessary to estimate normals. However, the normals are forgotten in the point cloud produced by the registration stage. Later on, when triangulating the cloud, the normals are re-estimated on the modified data, thus introducing uncontrollable errors.

We plan to develop new reconstruction, meshing and re-meshing algorithms, with a specific focus on the accuracy and resistance to all defects present in the input raw data. We think that pervasive treatment of uncertainty is the missing ingredient to achieve this goal. We plan to rethink the pipeline with the position uncertainty maintained during the whole process. Input points can be considered either as error ellipsoids [54] or as probability measures [36]. In a nutshell, our idea is to start by computing an error ellipsoid [56, 41] for each point of the raw data, and then to cumulate the errors (approximations) committed at each step of the processing pipeline while building the mesh. In this way, the final users will be able to take the uncertainty knowledge into account and rely on this confidence measure for further analysis and simulations. Quantifying uncertainty for reconstruction algorithms, and propagating them from input data to high-level geometry processing algorithms has never been considered before, possibly due to the very different methodologies of the approaches involved. At the very beginning we will re-implement the entire pipeline, and then attack the weak links through all three reconstruction stages.

3.2 Parameterizations

One of the favorite tools we use in our team are parameterizations. They provide a very powerful way to reveal structures on objects. The most omnipresent application of parameterizations is texture mapping: texture maps provide a way to represent in 2D (on the map) information related to a surface. Once the

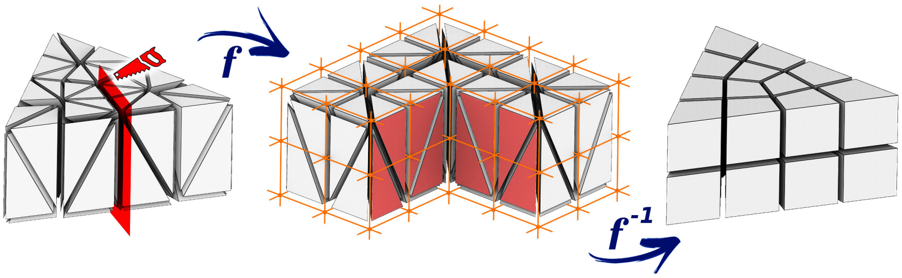

Figure 2: Hex-remeshing via global parameterization. **Left:** Input tetrahedral mesh. To allow for a singular edge in the center, the mesh is cut open along the red plane. **Middle:** Mesh in parametric space. **Right:** Output mesh defined by parameterization.

surface is equipped with a map, we can do much more than a mere coloring of the surface: we can approximate geodesics, edit the mesh directly in 2D or transfer information from one mesh to another.

Parameterizations constitute a family of methods that involve optimizing an objective function, subject to a set of constraints (equality, inequality, being integer, etc.). Computing the exact solution to such problems is beyond any hope, therefore approximations are the only resort. This raises a number of problems, such as the minimization of highly nonlinear functions and the definition of direction fields topology, without forgetting the robustness of the software that puts all this into practice.

We are particularly interested in a specific instance of parameterization: hexahedral meshing. The idea [4] is to build a transformation f from the domain to a parametric space, where the deformed domain can be meshed by a regular grid. The inverse transformation f^{-1} applied to this grid produces the hexahedral mesh of the domain, aligned with the boundary of the object. The strength of this approach is that the transformation may admit some discontinuities. Let us show an example: we start from a tetrahedral mesh (Figure 2, left) and we want deform it in a way that its boundary is aligned with the integer grid. To allow for a singular edge in the output (the valency 3 edge, Figure 2, right), the input mesh is cut open along the highlighted faces and the central edge is mapped onto an integer grid line (Figure 2, middle). The regular integer grid then induces the hexahedral mesh with the desired topology.

Current global parameterizations allow grids to be positioned inside geometrically simple objects whose internal structure (the singularity graph) can be relatively basic. We wish to be able to handle more configurations by improving three aspects of current methods:

- Local grid orientation is usually prescribed by minimizing the curvature of a 3D steering field. Unfortunately, this heuristic does not always provide singularity curves that can be integrated by the parameterization. We plan to explore how to embed integrability constraints in the generation of the direction fields. To address the problem, we already identified necessary validity criteria, for example, the permutation of axes along elementary cycles that go around a singularity must preserve one of the axes (the one tangent to the singularity). The first step to enforce this (necessary) condition will be to split the frame field generation into two parts: first we will define a locally stable vector field, followed by the definition of the other two axes by a 2.5D directional field (2D advected by the stable vector field).

- The grid combinatorial information is characterized by a set of integer coefficients whose values are currently determined through numerical optimization of a geometric criterion: the shape of the hexahedra must be as close as possible to the steering direction field. Thus, the number of layers of hexahedra between two surfaces is determined solely by the size of the hexahedra that one wishes to generate. In this setting degenerate configurations arise easily, and we want to avoid them. In practice, mixed integer solvers often choose to allocate a negative or zero number of layers of hexahedra between two constrained sheets (boundaries of the object, internal constraints or singularities). We will study how to inject strict positivity constraints into these cases, which is a very complex problem because of the subtle interplay between different degrees of freedom of the system. Our first results for quad-meshing of surfaces give promising leads, notably thanks to *motorcycle graphs* [30], a notion we wish to extend to volumes.

- Optimization for the geometric criterion makes it possible to control the average size of the hexahedra, but it does not ensure the bijectivity (even locally) of the resulting parameterizations. Considering other criteria, as we did in 2D [37], would probably improve the robustness of the process. Our idea is to keep the geometry criterion to find the global topology, but try other criteria to improve the geometry.

3.3 Hexahedral-dominant meshing

All global parameterization approaches are decomposed into three steps: frame field generation, field integration to get a global parameterization, and final mesh extraction. Getting a full hexahedral mesh from a global parameterization means that it has positive Jacobian everywhere except on the frame field singularity graph. To our knowledge, there is no solution to ensure this property, but some efforts are done to limit the proportion of failure cases. An alternative is to produce hexahedral dominant meshes. Our position is in between those two points of view:

1. We want to produce full hexahedral meshes;
2. We consider as pragmatic to keep hexahedral dominant meshes as a fallback solution.

The global parameterization approach yields impressive results on some geometric objects, which is encouraging, but not yet sufficient for numerical analysis. Note that while we attack the remeshing with our parameterizations toolset, the wish to improve the tool itself (as described above) is orthogonal to the effort we put into making the results usable by the industry. To go further, our idea (as opposed to [42, 31]) is that the global parameterization should not handle all the remeshing, but merely act as a guide to fill a large proportion of the domain with a simple structure; it must cooperate with other remeshing bricks, especially if we want to take final application constraints into account.

For each application we will take as an input domains, sets of constraints and, eventually, fields (e.g. the magnetic field in a tokamak). Having established the criteria of mesh quality (per application!) we will incorporate this input into the mesh generation process, and then validate the mesh by a numerical simulation software.

4 Application domains

4.1 Geometric Tools for Simulating Physics with a Computer

Numerical simulation is the main targeted application domain for the geometry processing tools that we develop. Our mesh generation tools will be tested and evaluated within the context of our cooperation with Hutchinson, experts in vibration control, fluid management and sealing system technologies. We think that the hex-dominant meshes that we generate have geometrical properties that make them suitable for some finite element analyses, especially for simulations with large deformations.

We also have a tight collaboration with, a geophysical modeling specialists via RING consortium. In particular, we produce hexahedral-dominant meshes for geomechanical simulations of gas and oil reservoirs. From a scientific point of view, this use case introduces new types of constraints (alignments with faults and horizons), and allows certain types of nonconformities that we did not consider until now.

Our cooperation with RhinoTerrain pursues the same goal: reconstruction of buildings from point cloud scans allows to perform 3D analysis and studies on insolation, floods and wave propagation, wind and noise simulations necessary for urban planification.

5 Highlights of the year

5.1 Industrial transfer

In May 2020, we have launched a start-up Tessael with Wan-Chiu Li as the CEO. The company provides meshing solutions based on GeO2 technology, which has been developed since 2010 by ALICE/PIXEL, a joint undertaking between Inria and Loria. Through its new GeO2 geological meshing technology,

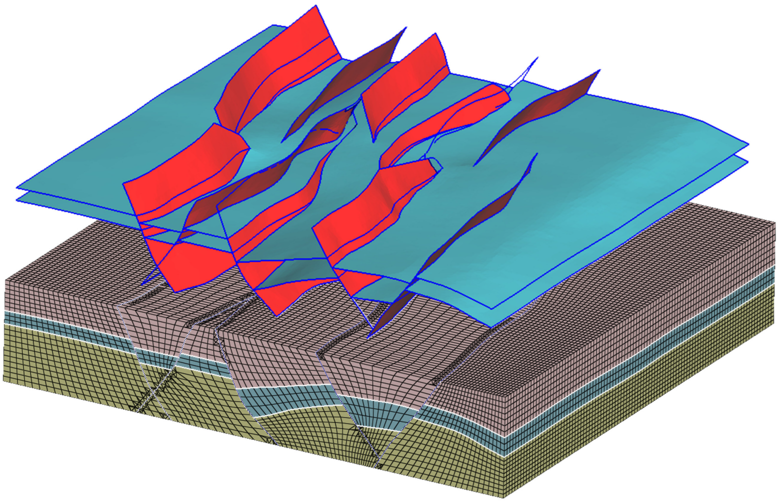

Figure 3: To run a numerical simulation, an underground space and its characteristic surfaces are divided up into geometric units, with the overall picture referred to as a “mesh”.

Tessael is able to perform and optimise extremely accurate 3D simulations of subsurface environments, opening up new opportunities in three sectors: geothermal energy, geological storage and the oil and gas industry. For these three key sectors, Tessael focuses on performing and optimising extremely accurate 3D simulations. GeO2 uses high quality meshes (refer to Figure 3) it generates, coupled with 3D visualisation technology, to make precise and accurate measurements within complex geological formations — a major breakthrough in the field of subsurface exploitation. GeO2 is also a decision-making aid for those operating in these industries, helping them minimise both environmental and financial risks while making exploration and production operations as efficient as possible.

5.2 Awards

- François Protais has received the best presentation award during GTMG2020[2]
- Guillaume Coiffier has received the 2nd prize for his paper presented at JFIG2020[3].

6 New results

6.1 Frame fields and parameterization

As we have mentioned in § 3.2, all global parameterization approaches are decomposed into three steps (refer to Fig. 4):

1. *Frame field generation:* this step defines the orientation of the grid at each point of the domain.
2. *Field integration:* this step computes the position and the size of the grid cells aligned with the input orientation field.
3. *Final mesh extraction:* at this step we map the grid onto the original object, thus creating the final quad/hex mesh.

We have new results for all three steps.

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[2] `https://gtmg2020.sciencesconf.org/`

[3] `https://jfig2020.sciencesconf.org/`

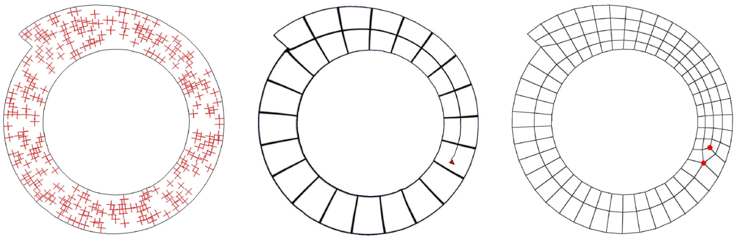


Figure 4: Quad meshing via global parameterization. **Left:** a cross field prescribing the orientation of the elements. **Middle:** a parameterization prescribing the size and the position of the elements to place. Note that it is *not* a quad mesh, it is a unit grid texture image mapped to the triangle mesh. In this case it is a periodic global parameterization, the red triangle shows a singularity of the parameterization. **Right:** a quad mesh extracted from the parameterization. The singularity of the parameterization corresponds to a dipole (a pair of vertices of valence 3 and 5, shown in red).

Frame field generation The generation of frame fields is a key component of recent quad meshing algorithms based on global parameterization, as it defines the orientation of the final facets. State-of-the-art methods are able to generate smooth frame fields subject to some hard constraints (direction and topology) or smooth constraints (matching the curvature direction). When dealing with CAD models, the field must be aligned with feature edges. Unfortunately, the smoothest frame field that respects this constraint have a topology that is considered as degenerate for producing quad meshes. More precisely, most CAD models contains at least one sharp corner i.e. a conflicting feature edge configuration, that would produce unmeshable cartographic pole in the frame field. Our preliminary results [19, 17] trade some smoothness against preventing generation of such singularities: we change the objective function to increase the cost of producing these singularities. We also relax the frame field orthogonality constraint that induces too much distortion on CAD objects.

Parameterization The parameterization step consists in integrating the frame field, while imposing integer constraints at the boundary and singular points. More precisely, one needs to find two scalar functions whose gradients are as close as possible to the input frame field under the integer constraints. When succeeding, these approaches provide impressive results. There are, however, many limitations. The frame field may not be integrable in the sense that is does not locally correspond to the gradient of a scalar function. This problem can be mitigated by asking the frame field to be curl-free. However this does not prevent a major problem: some frame fields are not consistent with any quadrangulation. Top left image of Fig. 4 provides an example: the radial frame field (without any singularities!) cannot be integrated directly; the only way to compute a parameterization is to insert a dipole (index 1/4 and -1/4) in the scalar fields. We have shown [11, 15] how a periodic global parameterization allows us to use recent cross field generation algorithms based on Ginzburg-Landau equations to accurately solve the parametrization step. We provide practical evidence that this formulation enables us to overcome common shortcomings in parametrization computation (inaccuracy away from the boundary, singular dipole placement).

Robust quantization for polycube maps An important part of recent advances in hexahedral meshing focus on the deformation of a domain into a polycube; the polycube deformed by the inverse map fills the domain with a hexahedral mesh. These methods are appreciated because they generate highly regular meshes. We have addressed [23] a robustness issue that systematically occurs when a coarse mesh is desired: algorithms produce deformations that are not one-to-one, leading to collapse of large portions of the model when trying to apply the (undefined) inverse map. The origin of the problem is that the deformation requires to perform a mixed integer optimization, where the difficulty to enforce the integer constraints is directly tied to the expected coarseness. Our solution is to introduce constraints that prevent the loss of bijectivity due to the integer constraints.

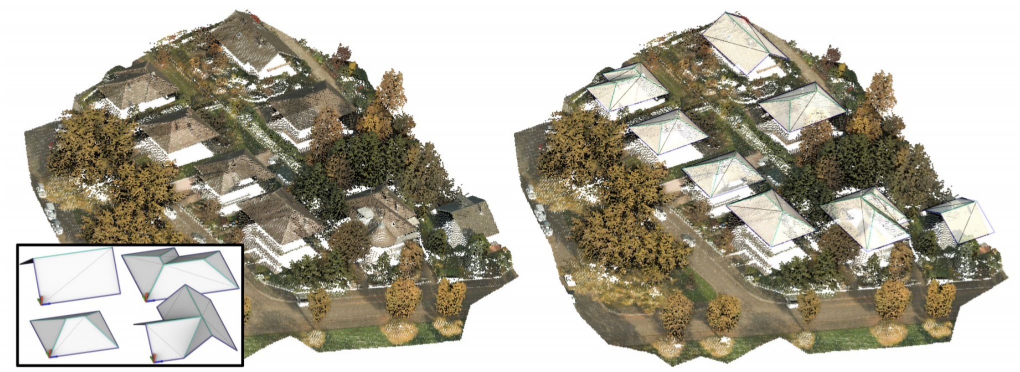


Figure 5: **Left:** Example of roofs and airborne LIDAR cloud models. **Right:** We are interested in fitting the user-defined models to the corresponding point cloud.

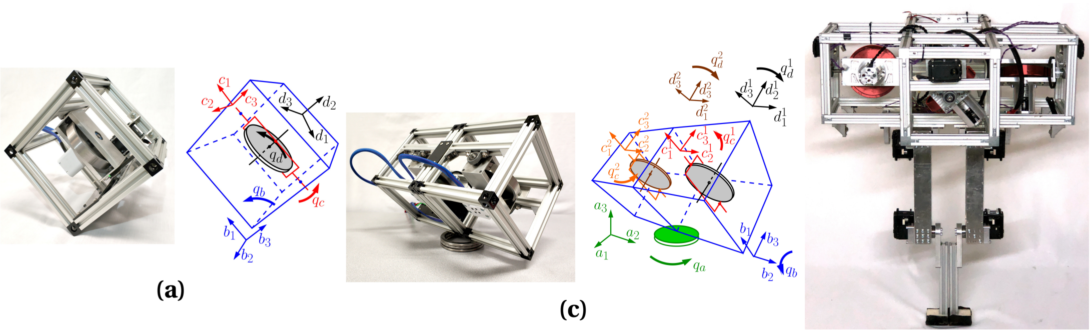
6.2 Roof fitting

This work is done as part of our contract between our team and RhinoTerrain. Automatic extraction of building roofs from remote sensing data is important for many applications including 3D city modeling, urban planning, disaster management, and simulations. In this project, we propose an automatic workflow for roof reconstruction by polygonal models from airbourne LIDAR data (Figure 5). This year we have published two papers on this subject [7, 16], and one more is currently under review. The main idea is to extend the VSDM algorithm (*Voronoï Squared Distance Minimization*) developed by the team [43] to the case of fitting parametric template models to point clouds. Using a high quality mesh as geometric template to fit a point cloud is a common practice to generate animation of faces or even full bodies from a depth camera. We are interested here to match the human-made objects whose acceptable deformations are not as rigid as possible, but rather described by a parametric template. The motivation is to be able to retrieve CAD objects or buildings in a point cloud. While it has a very broad applicability range, we are particularly interested in fitting roof templates to airborne LIDAR point clouds. Most previous works detect characteristic features (planes, ridges, contours) to combine them into a roof. We instead formulate it as a global fitting problem, and propose an efficient way to solve it. The originality of our approach is to fit a mesh with geometric constraints (a roof template) to the point cloud by a fast and robust numerical optimization. More precisely, we simultaneously consider the distance from the model to the point cloud, and the distance from the point cloud to the model, with a biweight estimator to integrate outliers rejection directly in our numerical optimization framework. With our formulation, we do not need to alternate between matching and fitting steps. The objective function being smooth everywhere, it can be minimized by quasi-Newtonian methods like L-BFGS. The advantage of our method is that the feature matching, roof trimming, point cloud segmentation, and integrity roof constraints are all supported in a unique numerical optimization problem that can be solved very efficiently.

6.3 Auxiliary stabilization systems for legged robots

This year marks the end of our robotics project that we have started with our Russian colleagues prior the creation of the team Pixel. We have worked on geometrical methods in automatic control, with an application to legged robotics. The overall idea of the project is to improve the stability of a robot while reducing the cost of its production.

While dynamic bipedal stabilization remains a challenging topic and a releveant benchmark for control design and a multitude of technological processes, a fulgurant progress in this area does not cease to amaze the public. Demands on leg degrees of freedom and control precision for bipedal robotics are steadily increasing, especially for the tasks involving walking on a rough terrain. It is only natural to wish to employ the finest possible parts, but this wish is intrinsically flawed and seldom justified. In fact, chasing down (inevitable!) mechanical imprecisions is equivalent to mimicking the nature: a human's gait is very precise thanks to the quality of the articulations. But if a human ever tears one his cruciate



(a)

(c)

(c)

Figure 6: We are developing a biped that uses four control moment gyroscopes (highlited in red in image **(c)**) as an auxiliary stabilization system. Starting from a simple 1D inverted pendulum **(a)**, we moved on to a 3D inverted pendulum **(b)**, and finally have created a walking biped **(c)**.

ligaments, the stability of the knee is immediately compromised. We do not want to mimic animals completely: at the moment we do not know how to build effective muscles, and backlash in artificial joints is almost inevitable. Too bad, robots have other advantages: for example, the rotational movement is very easy to implement. Since the dawn of time, man has wanted to fly, but airplanes do not flap their wings. Indeed, there is a way to enhance the robot's stability even in a presence of hard-to-model factors like backlashes, frictions and mechanical deformations. We can design auxiliary devices capable to improve the stability while performing complex tasks. We propose to give robots an additional "support point" without touching the rest of the mechanical system. We have created an electromechanical auxiliary stabilization system able to compensate for external disturbances and control errors with aid of control moment gyroscopes.

This year we have published a number of papers on the subject, including flagship journals and conferences such as Transactions on Automatic Control [8] and IFAC World Congress [12, 9]. A part of these publications is a conjoint work with Inria team Valse. To approach the problem, we have started by studying 1D inverted pendulums [12, 8, 9, 5, 13, 21, 10] (Fig. 6–a). Then we have moved to 3D inverted pendulums study [6, 14, 10] (Fig. 6–a). Our latest results on the biped (Fig. 6–c) are currently under review.

7 Bilateral contracts and grants with industry

7.1 Bilateral contracts with industry

- *Company:* Polygonal Design
  Duration: 01/02/2018 – 01/08/2020
  Participants: Bruno Lévy and Laurent Alonso
  Amount: 38k euros
  Abstract: The goal of this project is to provide a scientific and technical expertise to Polygonal Design. In particular this concerns the Unfold3d software, developed and marketed by the company. This software is built based on our algorithms developed in 2002–2006.

- *Company:* CEA
  Duration: 01/10/2019 – 30/09/2022
  Participants: Dmitry Sokolov, Nicolas Ray and François Protais
  Amount: 45k euros
  Abstract: This project revolves around generation of Polycubes guided by orientation fields. The first goal of the project is to define a new Polycube method that deforms an object along a previously generated 3D orientation field. Such a solution would overcome two major defects of Polycube methods, namely : (1) The possible absence of aligned mesh layers along the smooth edges; (2) The poor treatment of sharp edges (which is very common on mechanical parts in CAD).

- *Company:* RhinoTerrain
  Duration: 01/12/2019 – 30/03/2024
  Participants: Dmitry Sokolov, Nicolas Ray and Justine Basselin
  Amount: 50k euros
  Abstract: In this project, we are interested in the reconstruction phase in the context of LIDAR point clouds of city districts. These data are acquired via an airplane and contain every object present in the city: cars, trees, building roofs, roads and ground features, *etc.* Applications of these data, ranging from city visualization for tourism to flood and wind simulation, require the reconstruction of buildings as geometrical objects. As LIDAR point cloud are acquired from the sky, buildings are only represented by their roofs. Hence, determining the polygonal surfaces of roofs enables the reconstruction of the whole city by extrusion.

- *Company:* Total
  Duration: 01/10/2020 – 30/03/2024
  Participants: Dmitry Sokolov, Nicolas Ray and David Desobry
  Amount: confidential
  Abstract: The goal of this project is to improve the accuracy of rubber behavior simulations for certain parts produced by Total, notably gaskets. To do this, both parties need to develop meshing methods adapted to simulations of large deformation in non-linear mechanics. The Pixel team has a great expertise in hex-dominant meshing, Total has a strong background in numerical simulations within an industrial context. This collaborative project aims to take advantage of both expertises.

8 Dissemination

8.1 Promoting scientific activities

8.1.1 Scientific events: organisation

This year we have organized three scientific events:

- GTMG2020[4] (Groupe de Travail en Modélisation Géométrique, 55 participants);
- JFIG2020[5] (Journées Françaises d'Informatique Graphique, 120 participants);
- FRAMES2020[6] (50 participants, co-organized with UC Louvain).

Member of the conference program committees Members of the team were IPC members for SPM, ISVC and NUMGRID.

Reviewer Members of the team were reviewers for Eurographics, SIGGRAPH, SIGGRAPH Asia, ISVC, Pacific Graphics, and SPM.

8.1.2 Journal

Members of the team were reviewers for Computer Aided Design (CAD), Transactions on Visualization and Computer Graphics (IEEE), Transactions on Graphics (ACM), and Computers & Graphics (Elsevier).

Reviewer - reviewing activities

8.1.3 Invited talks

Dmitry Sokolov has given an invited talk at NUMGRID2020 (Numerical Geometry, Grid Generation and Scientific Computing) conference[7].

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[4] `https://gtmg2020.sciencesconf.org/`
[5] `https://jfig2020.sciencesconf.org/`
[6] `https://www.hextreme.eu/frames2020/`
[7] `https://numgrid.ru/numgrid2020/`

8.1.4 Research administration

Dmitry Sokolov is responsible for the Industrial Club of GdR IG-RV (Groupement de recherche Informatique Géométrique et Graphique, Réalité Virtuelle et Visualisation)[8].

8.2 Teaching - Supervision - Juries

8.2.1 Teaching

- Licence : Dobrina Boltcheva, Computer Graphics, 30h, 3A, IUT Saint-Dié-des-Vosges
- Licence : Dobrina Boltcheva, Advanced Object Oriented Programming & UML, 60h, 2A, IUT SaintDié-des-Vosges
- Licence : Dobrina Boltcheva, Advanced algorithmics, 50h, 2A, IUT Saint-Dié-des-Vosges
- Licence : Dobrina Boltcheva, Image Processing, 30h, 2A, IUT Saint-Dié-des-Vosges
- Licence : Dobrina Boltcheva, UML Modeling, 20h, 1A, IUT Saint-Dié-des-Vosges
- Licence : Dobrina Boltcheva, Algorithmics, 30h, 3A, PolyTech Nancy
- Licence : Dobrina Boltcheva, Computer Graphics, 12h, 5A, PolyTech Nancy
- License : Guillaume Coiffier, Programming in python, 16h, 1A, University of Lorraine
- Master : François Protais, 3D data visualization, 12h, M1, University of Lorraine
- Master : François Protais, Software engineering, 16h, M1, University of Lorraine
- Licence : Dmitry Sokolov, Programming, 26h, 2A, University of Lorraine
- Licence : Dmitry Sokolov, Logic, 30h, 3A, University of Lorraine
- Master : Dmitry Sokolov, Logic, 22h, M1, University of Lorraine
- Master : Dmitry Sokolov, Computer Graphics, 12h, M1, University of Lorraine
- Master : Dmitry Sokolov, 3D data visualization, 15h, M1, University of Lorraine
- Master : Dmitry Sokolov, 3D printing, 12h, M2, University of Lorraine
- Master : Dmitry Sokolov, Numerical modeling, 12h, M2, University of Lorraine

8.2.2 Supervision

- PhD in progress: David Lopez, *"Voronoi diagrams and moving surfaces"*, since November 2020, Dmitry Sokolov and Nicolas Ray.
- PhD in progress: Guillaume Coiffier, *"Improving global parameterization algorithms"*, since September 2020, Dmitry Sokolov and Etienne Corman.
- PhD in progress: David Desobry, *"Quad meshing for large deformation sumulations"*, since September 2020, Dmitry Sokolov, Nicolas Ray and Jeanne Pellerin.
- PhD in progress: Justine Basselin, *"Reconstruction of buildings from 3D point clouds"*, since December 2019, Dmitry Sokolov, Nicolas Ray and Hervé Barthélémy.
- PhD in progress: François Protais, *"Polycube-dominant meshing"*, since October 2019, Dmitry Sokolov and Franck Ledoux.

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[8] `https://gdr-igrv.icube.unistra.fr/`

8.2.3 Juries

Dmitry Sokolov participated in the PhD jury of Sinetova Madina (ITMO, Saint Petersburg, Russia) as an examinator.

9 Scientific production

9.1 Major publications

[1] N. Ray and D. Sokolov. 'Robust Polylines Tracing for N-Symmetry Direction Field on Triangulated Surfaces'. In: *ACM Trans. Graph.* 33.3 (June 2014), 30:1–30:11. DOI: 10.1145/2602145. URL: http://doi.acm.org/10.1145/2602145.

[2] N. Ray, D. Sokolov, S. Lefebvre and B. Lévy. 'Meshless Voronoi on the GPU'. In: *ACM Trans. Graph.* 37.6 (Dec. 2018), 265:1–265:12. DOI: 10.1145/3272127.3275092. URL: http://doi.acm.org/10.1145/3272127.3275092.

[3] N. Ray, D. Sokolov and B. Lévy. 'Practical 3D Frame Field Generation'. In: *ACM Trans. Graph.* 35.6 (Nov. 2016), 233:1–233:9. DOI: 10.1145/2980179.2982408. URL: http://doi.acm.org/10.1145/2980179.2982408.

[4] D. Sokolov, N. Ray, L. Untereiner and B. Lévy. 'Hexahedral-Dominant Meshing'. In: *ACM Transactions on Graphics* 35.5 (2016), pp. 1–23. DOI: 10.1145/2930662. URL: https://hal.inria.fr/hal-01397846.

9.2 Publications of the year

International journals

[5] S. Aranovskiy, I. Ryadchikov, E. Nikulchev, J. Wang and D. Sokolov. 'Bias Propagation and Estimation in Homogeneous Differentiators for a Class of Mechanical Systems'. In: *IEEE Access* 8 (2020), pp. 19450–19459. DOI: 10.1109/ACCESS.2020.2968219. URL: https://hal-centralesupelec.archives-ouvertes.fr/hal-02516559.

[6] S. Aranovskiy, I. Ryadchikov, E. Nikulchev, J. Wang and D. Sokolov. 'Experimental Comparison of Velocity Observers: A Scissored Pair Control Moment Gyroscope Case Study'. In: *IEEE Access* 8 (2020), pp. 21694–21702. DOI: 10.1109/ACCESS.2020.2968221. URL: https://hal-centralesupelec.archives-ouvertes.fr/hal-02516558.

[7] D. Boltcheva, J. Basselin, C. Poull, H. Barthelemy and D. Sokolov. 'Topological-based roof modeling from 3D point clouds'. In: *Journal of WSCG* 28.1-2 (2020), pp. 137–146. DOI: 10.24132/JWSCG.2020.28.17. URL: https://hal.archives-ouvertes.fr/hal-02983073.

[8] J. Wang, S. Aranovskiy, E. Fridman, D. Sokolov, D. Efimov and A. Bobtsov. 'Robust adaptive stabilization by delay under state parametric uncertainty and measurement bias'. In: *IEEE Transactions on Automatic Control* (2020). DOI: 10.1109/TAC.2020.3045125. URL: https://hal.inria.fr/hal-03059893.

International peer-reviewed conferences

[9] S. Aranovskiy, D. Efimov, D. Sokolov, J. Wang, I. Ryadchikov and A. Bobtsov. 'State estimation for a locally unobservable parameter-varying system: one gradient-based and one switched solutions'. In: IFAC 2020 - 21rst IFAC World Congress. Berlin, Germany, 13th July 2020. URL: https://hal.inria.fr/hal-02634576.

[10] S. Aranovskiy, I. Ryadchikov, N. Mikhalkov, D. Kazakov, A. Simulin and D. Sokolov. 'Scissored pair control moment gyroscope inverted pendulum'. In: 14th International Symposium "Intelligent Systems - 2020". Moscow, Russia, 14th Dec. 2020. URL: https://hal.inria.fr/hal-02985412.

[11] V. Blanchi, E. Corman, N. Ray and D. Sokolov. 'Global parametrization based on Ginzburg-Landau functional'. In: NUMGRID 2020 — Numerical Geometry, Grid Generation and Scientific Computing. Moscow/Virtual, Russia, 25th Nov. 2020. URL: https://hal.inria.fr/hal-02985282.

[12] D. Efimov, S. Aranovskiy, E. Fridman, D. Sokolov, J. Wang and A. Bobtsov. 'Adaptive stabilization by delay with biased measurements'. In: IFAC 2020 - 21st IFAC World Congress. Berlin, Germany, 11th July 2020. URL: https://hal.inria.fr/hal-02634582.

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National peer-reviewed Conferences

[15] V. Blanchi, E. Corman, N. Ray and D. Sokolov. 'Génération de maillage quadrangulaire d'un domaine du plan via les équations de Ginzburg-Landau'. In: Journées Françaises d'Informatique Graphique (JFIG2020). Nancy, France, 25th Nov. 2020. URL: https://hal.inria.fr/hal-02992599.

[16] G. Coiffier, J. Basselin, N. Ray and D. Sokolov. 'Ajustement de surfaces paramétriques sur nuages de points'. In: Journées Françaises d'Informatique Graphique (JFIG2020). Nancy, France, 25th Nov. 2020. URL: https://hal.inria.fr/hal-02992607.

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[19] F. Protais, E. Corman, N. Ray and D. Sokolov. 'Champs de repères pour les modèles CAO'. In: Journées Françaises d'Informatique Graphique (JFIG2020). Vol. xx. Nancy, France, 25th Nov. 2020, pp. 1–5. URL: https://hal.inria.fr/hal-02992612.

Scientific books

[20] C. Gentil, G. Gouaty and D. Sokolov. *Modélisation géométrique de formes fractales pour la CAO.* 15th Jan. 2020. URL: https://hal-univ-bourgogne.archives-ouvertes.fr/hal-02462416.

Scientific book chapters

[21] I. Ryadchikov, S. Sechenev, N. Mikhalkov, A. Biryuk, A. Svidlov, A. Gusev, D. Sokolov and E. Nikulchev. 'Feedback Control with Equilibrium Revision for CMG-Actuated Inverted Pendulum'. In: *Proceedings of 14th International Conference on Electromechanics and Robotics "Zavalishin's Readings".* 30th Aug. 2020, pp. 431–440. DOI: 10.1007/978-981-13-9267-2_35. URL: https://hal.inria.fr/hal-02282908.

Reports & preprints

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9.3 Cited publications

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