Activity Report 2017

Project-Team TITANE

Geometric Modeling of 3D Environments

RESEARCH CENTER
Sophia Antipolis - Méditerranée

THEME
Interaction and visualization

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Project-Team TITANE

Creation of the Team: 2013 January 01, updated into Project-Team: 2014 January 01

Keywords:

Computer Science and Digital Science:

A5.3. - Image processing and analysis
A5.4.4. - 3D and spatio-temporal reconstruction
A5.5.1. - Geometrical modeling
A8.3. - Geometry, Topology

Other Research Topics and Application Domains:

B3.3. - Geosciences
B5. - Industry of the future
B8. - Smart Cities and Territories

1. Personnel

Research Scientists

Pierre Alliez [Team leader, Inria, Senior Researcher, HDR]
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Florent Lafarge [Inria, Researcher, HDR]
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Hao Fang [Inria]
Jean-Dominique Favreau [Univ de Nice - Sophia Antipolis, until Sep 2017]
Nicolas Girard [Inria, from Nov 2017]
Emmanuel Maggiori [Inria, until Jul 2017]
Lionel Matteo [Geoazur, from Sep 2017]
Onur Tasar [Inria, from Oct 2017]

Technical staff

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Cedric Portaneri [Inria]

Interns

Leihan Chen [Inria, from Jul 2017 until Nov 2017]
Leman Feng [Inria, from Mar 2017 until Aug 2017]
Armand Zampieri [Inria, from Apr 2017 until Sep 2017]

Administrative Assistant

Florence Barbara [Inria]

Visiting Scientists

David Bommes [RWTH Aachen, Sep 2017]
Gianmarco Cherchi [University of Cagliary, from Sep 2017]
Vinay Renigunta [Hyderabad, from May 2017 until Jul 2017]
Alena Schmidt [ETZ Zürich, from Mar 2017 until Apr 2017]

2. Overall Objectives

2.1. General Presentation

Our overall objective is the computerized geometric modeling of complex scenes from physical measurements. On the geometric modeling and processing pipeline, this objective corresponds to steps required for conversion from physical to effective digital representations: *analysis*, *reconstruction* and *approximation*. Another longer term objective is the *synthesis* of complex scenes. This objective is related to analysis as we assume that the main sources of data are measurements, and synthesis is assumed to be carried out from samples.

The related scientific challenges include i) being resilient to defect-laden data due to the uncertainty in the measurement processes and imperfect algorithms along the pipeline, ii) being resilient to heterogeneous data, both in type and in scale, iii) dealing with massive data, and iv) recovering or preserving the structure of complex scenes. We define the quality of a computerized representation by its i) geometric accuracy, or faithfulness to the physical scene, ii) complexity, iii) structure accuracy and control, and iv) amenability to effective processing and high level scene understanding.

3. Research Program

3.1. Context

Geometric modeling and processing revolve around three main end goals: a computerized shape representation that can be visualized (creating a realistic or artistic depiction), simulated (anticipating the real) or realized (manufacturing a conceptual or engineering design). Aside from the mere editing of geometry, central research themes in geometric modeling involve conversions between physical (real), discrete (digital), and mathematical (abstract) representations. Going from physical to digital is referred to as shape acquisition and reconstruction; going from mathematical to discrete is referred to as shape approximation and mesh generation; going from discrete to physical is referred to as shape rationalization.

Geometric modeling has become an indispensable component for computational and reverse engineering. Simulations are now routinely performed on complex shapes issued not only from computer-aided design but also from an increasing amount of available measurements. The scale of acquired data is quickly growing: we no longer deal exclusively with individual shapes, but with entire *scenes*, possibly at the scale of entire cities, with many objects defined as structured shapes. We are witnessing a rapid evolution of the acquisition paradigms with an increasing variety of sensors and the development of community data, as well as disseminated data.

In recent years, the evolution of acquisition technologies and methods has translated in an increasing overlap of algorithms and data in the computer vision, image processing, and computer graphics communities. Beyond the rapid increase of resolution through technological advances of sensors and methods for mosaicing images, the line between laser scan data and photos is getting thinner. Combining, e.g., laser scanners with panoramic cameras leads to massive 3D point sets with color attributes. In addition, it is now possible to generate dense point sets not just from laser scanners but also from photogrammetry techniques when using a well-designed acquisition protocol. Depth cameras are getting increasingly common, and beyond retrieving depth information we can enrich the main acquisition systems with additional hardware to measure geometric information about the sensor and improve data registration: e.g., accelerometers or GPS for geographic location, and compasses or gyrometers for orientation. Finally, complex scenes can be observed at different scales ranging from satellite to pedestrian through aerial levels.

These evolutions allow practitioners to measure urban scenes at resolutions that were until now possible only at the scale of individual shapes. The related scientific challenge is however more than just dealing with massive data sets coming from increase of resolution, as complex scenes are composed of multiple objects with structural relationships. The latter relate i) to the way the individual shapes are grouped to form objects, object classes or hierarchies, ii) to geometry when dealing with similarity, regularity, parallelism or symmetry, and iii) to domain-specific semantic considerations. Beyond reconstruction and approximation, consolidation and synthesis of complex scenes require rich structural relationships.

The problems arising from these evolutions suggest that the strengths of geometry and images may be combined in the form of new methodological solutions such as photo-consistent reconstruction. In addition, the process of measuring the geometry of sensors (through gyrometers and accelerometers) often requires both geometry process and image analysis for improved accuracy and robustness. Modeling urban scenes from measurements illustrates this growing synergy, and it has become a central concern for a variety of applications ranging from urban planning to simulation through rendering and special effects.

3.2. Analysis

Complex scenes are usually composed of a large number of objects which may significantly differ in terms of complexity, diversity, and density. These objects must be identified and their structural relationships must be recovered in order to model the scenes with improved robustness, low complexity, variable levels of details and ultimately, semantization (automated process of increasing degree of semantic content).

Object classification is an ill-posed task in which the objects composing a scene are detected and recognized with respect to predefined classes, the objective going beyond scene segmentation. The high variability in each class may explain the success of the stochastic approach which is able to model widely variable classes. As it requires a priori knowledge this process is often domain-specific such as for urban scenes where we wish to distinguish between instances as ground, vegetation and buildings. Additional challenges arise when each class must be refined, such as roof super-structures for urban reconstruction.

Structure extraction consists in recovering structural relationships between objects or parts of object. The structure may be related to adjacencies between objects, hierarchical decomposition, singularities or canonical geometric relationships. It is crucial for effective geometric modeling through levels of details or hierarchical multiresolution modeling. Ideally we wish to learn the structural rules that govern the physical scene manufacturing. Understanding the main canonical geometric relationships between object parts involves detecting regular structures and equivalences under certain transformations such as parallelism, orthogonality and symmetry. Identifying structural and geometric repetitions or symmetries is relevant for dealing with missing data during data consolidation.

Data consolidation is a problem of growing interest for practitioners, with the increase of heterogeneous and defect-laden data. To be exploitable, such defect-laden data must be consolidated by improving the data sampling quality and by reinforcing the geometrical and structural relations sub-tending the observed scenes. Enforcing canonical geometric relationships such as local coplanarity or orthogonality is relevant for registration of heterogeneous or redundant data, as well as for improving the robustness of the reconstruction process.

3.3. Approximation

Our objective is to explore the approximation of complex shapes and scenes with surface and volume meshes, as well as on surface and domain tiling. A general way to state the shape approximation problem is to say that we search for the shape discretization (possibly with several levels of detail) that realizes the best complexity / distortion trade-off. Such a problem statement requires defining a discretization model, an error metric to measure distortion as well as a way to measure complexity. The latter is most commonly expressed in number of polygon primitives, but other measures closer to information theory lead to measurements such as number of bits or minimum description length.

For surface meshes we intend to conceive methods which provide control and guarantees both over the global approximation error and over the validity of the embedding. In addition, we seek for resilience to heterogeneous data, and robustness to noise and outliers. This would allow repairing and simplifying triangle soups with cracks, self-intersections and gaps. Another exploratory objective is to deal generically with different error metrics such as the symmetric Hausdorff distance, or a Sobolev norm which mixes errors in geometry and normals.

For surface and domain tiling the term meshing is substituted for tiling to stress the fact that tiles may be not just simple elements, but can model complex smooth shapes such as bilinear quadrangles. Quadrangle surface tiling is central for the so-called *resurfacing* problem in reverse engineering: the goal is to tile an input raw surface geometry such that the union of the tiles approximates the input well and such that each tile matches certain properties related to its shape or its size. In addition, we may require parameterization domains with a simple structure. Our goal is to devise surface tiling algorithms that are both reliable and resilient to defect-laden inputs, effective from the shape approximation point of view, and with flexible control upon the structure of the tiling.

3.4. Reconstruction

Assuming a geometric dataset made out of points or slices, the process of shape reconstruction amounts to recovering a surface or a solid that matches these samples. This problem is inherently ill-posed as infinitely-many shapes may fit the data. One must thus regularize the problem and add priors such as simplicity or smoothness of the inferred shape.

The concept of geometric simplicity has led to a number of interpolating techniques commonly based upon the Delaunay triangulation. The concept of smoothness has led to a number of approximating techniques that commonly compute an implicit function such that one of its isosurfaces approximates the inferred surface. Reconstruction algorithms can also use an explicit set of prior shapes for inference by assuming that the observed data can be described by these predefined prior shapes. One key lesson learned in the shape problem is that there is probably not a single solution which can solve all cases, each of them coming with its own distinctive features. In addition, some data sets such as point sets acquired on urban scenes are very domain-specific and require a dedicated line of research.

In recent years the *smooth, closed case* (i.e., shapes without sharp features nor boundaries) has received considerable attention. However, the state-of-the-art methods have several shortcomings: in addition to being in general not robust to outliers and not sufficiently robust to noise, they often require additional attributes as input, such as lines of sight or oriented normals. We wish to devise shape reconstruction methods which are both geometrically and topologically accurate without requiring additional attributes, while exhibiting resilience to defect-laden inputs. Resilience formally translates into stability with respect to noise and outliers. Correctness of the reconstruction translates into convergence in geometry and (stable parts of) topology of the reconstruction with respect to the inferred shape known through measurements.

Moving from the smooth, closed case to the *piecewise smooth case* (possibly with boundaries) is considerably harder as the ill-posedness of the problem applies to each sub-feature of the inferred shape. Further, very few approaches tackle the combined issue of robustness (to sampling defects, noise and outliers) and feature reconstruction.

4. Application Domains

4.1. Applications

In addition to tackling enduring scientific challenges, our research on geometric modeling and processing is motivated by applications to computational engineering, reverse engineering, digital mapping and urban planning. The main deliverable of our research will be algorithms with theoretical foundations. Ultimately we wish to contribute making geometry modeling and processing routine for practitioners who deal with real-world data. Our contributions may also be used as a sound basis for future software and technology developments.

Our first ambition for technology transfer is to consolidate the components of our research experiments in the form of new software components for the CGAL (Computational Geometry Algorithms Library) library. Consolidation being best achieved with the help of an engineer, we will search for additional funding. Through CGAL we wish to contribute to the “standard geometric toolbox”, so as to provide a generic answer to application needs instead of fragmenting our contributions. We already cooperate with the Inria spin-off company Geometry Factory, which commercializes CGAL, maintains it and provide technical support.

Our second ambition is to increase the research momentum of companies through advising Cifre Ph.D. theses and postdoctoral fellows on topics that match our research program.

5. Highlights of the Year

5.1. Highlights of the Year

We obtained five ANR grants end of 2017, including a young researcher grant EPITOME (principal investigator Yuliya Tarabalka). We started a collaboration with the Google Chrome/Youtube team, on the progressive compression of 3D models.

Pierre Alliez is now a member of the Steering Committee of the EUROGRAPHICS Symposium on Geometry Processing. He was also elected Executive Board Member for the Solid Modeling Association, for 4 years.

6. New Software and Platforms

6.1. CGAL Barycentric_coordinates_2

Module CGAL : Barycentric coordinates 2D
KEYWORD: Computational geometry
FUNCTIONAL DESCRIPTION: This package offers an efficient and robust implementation of two-dimensional closed-form generalized barycentric coordinates defined for simple two-dimensional polygons.

- Participants: Dmitry Anisimov and Pierre Alliez
- Contact: Pierre Alliez

6.2. dtk-nurbs-probing

KEYWORDS: Algorithm - CAD - Numerical algorithm - Geometric algorithms
FUNCTIONAL DESCRIPTION: This library offers tools for computing intersection between linear primitives and the constitutive elements of CAD objects (curves and surfaces). It is thus possible to compute intersections between a linear primitive with a trimmed or untrimmed NURBS surface, as well with Bezier surfaces. It is also possible, in the xy plane, to compute the intersections between linear primitives and NURBS curves as well as Bezier curves.

- Participants: Come Le Breton, Laurent Busé and Pierre Alliez
- Contact: Come Le Breton

6.3. MeshMantics

KEYWORDS: Classification - 3D modeling
FUNCTIONAL DESCRIPTION: This software component enables the classification of surface meshes in accordinace to common outdoor urban classes such as ground, facades, walls, roofs and vegetation.

- Participants: Florent Lafarge, Pierre Alliez and Yannick Verdié
- Contact: Pierre Alliez

6.4. Module CGAL : Point Set Processing

KEYWORD: Geometry Processing
FUNCTIONAL DESCRIPTION: This CGAL component implements methods to analyze and process unorganized point sets. The input is an unorganized point set, possibly with normal attributes (unoriented or oriented). The point set can be analyzed to measure its average spacing, and processed through functions devoted to the simplification, outlier removal, smoothing, normal estimation, normal orientation and feature edges estimation.

- Participants: Clément Jamin, Laurent Saboret and Pierre Alliez
- Contact: Pierre Alliez
- URL: http://doc.cgal.org/latest/Point_set_processing_3/index.html#Chapter_Point_Set_Processing

6.5. Module CGAL : Scale space surface reconstruction

KEYWORD: Geometric algorithms
SCIENTIFIC DESCRIPTION: This CGAL package implements a surface reconstruction method which takes as input an unordered point set and computes a triangulated surface mesh interpolating the point set. We assume that the input points were sampled from the surface of an object. The method can also process point sets sampled from the interior of the object, although we cannot provide guarantees on the output. This method can handle a decent amount of noise and outliers. The point set may greatly undersample the object in occluded regions, although no surface will be reconstructed to fill these regions.
FUNCTIONAL DESCRIPTION: This method allows to reconstruct a surface that interpolates a set of 3D points. This method provides an efficient alternative to the Poisson surface reconstruction method. The main difference in output is that this method reconstructs a surface that interpolates the point set (as opposed to approximating the point set). How the surface connects the points depends on a scale variable, which can be estimated semi-automatically.

- Participants: Pierre Alliez and Thijs Van Lankveld
- Contact: Pierre Alliez

6.6. Skeleton-Blockers

Skeleton-Blockers data-structure
KEYWORDS: Topology - Triangulation - Mesh - C++ - 3D
FUNCTIONAL DESCRIPTION: Skeleton-Blockers is a compact, efficient and generic data-structure that can represent any simplicial complex. The implementation is in C++11.

- Participant: David Salinas
- Contact: David Salinas
- URL: https://project.inria.fr/gudhi/software/

6.7. Structure-preserving decimation

KEYWORDS: Mesh - 3D - Multi-View reconstruction
FUNCTIONAL DESCRIPTION: Structure-preserving decimation is a software that can simplify 3D meshes while preserving some of their structure. Simplification can be done either with a command line or with a graphical user interface that allows to combine several operations including several simplification methods.

- Participants: David Salinas, Florent Lafarge and Pierre Alliez
- Contact: David Salinas

7. New Results

7.1. Analysis

7.1.1. Forest point processes for line-network extraction

Participants: Alena Schmidt, Florent Lafarge.

In collaboration with Claus Brenner, Franz Rottensteiner and Christian Heipke from the Leibniz Universitat Hannover, Germany.

We contributed a new stochastic approach for the automatic detection of network structures in raster data. We represent a network as a set of trees with acyclic planar graphs. We embed this model in the probabilistic framework of spatial point processes and determine the most probable configuration of trees by stochastic sampling. That is, different configurations are constructed randomly by modifying the graph parameters and by adding or removing nodes and edges to or from the current trees. Each configuration is evaluated based on the probabilities for these changes and an energy function describing the conformity with a predefined model. Although our main target application is the extraction of rivers and tidal channels in digital terrain models as illustrated on Figure 1, experiments with other types of networks in images show the transferability to further applications. Qualitative and quantitative evaluations demonstrate the competitiveness of our approach with respect to existing algorithms. This work was published in the ISPRS journal [21].

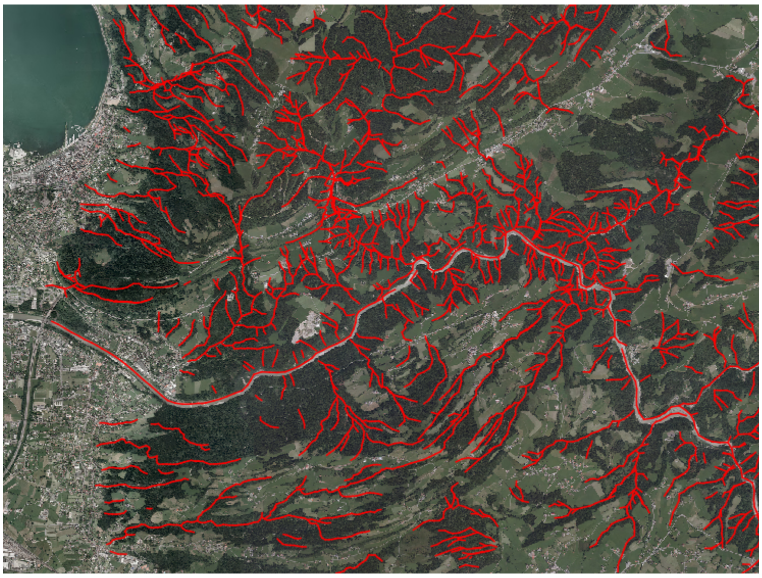

Figure 1. Extraction of line-networks by Forest point processes. River network is represented by acyclic planar graphs in red.

7.1.2. Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients

Participants: Jean-Dominique Favreau, Florent Lafarge.

In collaboration with Adrien Bousseau (GraphDeco Inria team)

We proposed a method to create vector cliparts from photographs. Our approach aims at reproducing two key properties of cliparts: they should be easily editable, and they should represent image content in a clean, simplified way. We observe that vector artists satisfy both of these properties by modeling cliparts with linear color gradients, which have a small number of parameters and approximate well smooth color variations. In addition, skilled artists produce intricate yet editable artworks by stacking multiple gradients using opaque and semi-transparent layers. Motivated by these observations, our goal is to decompose a bitmap photograph into a stack of layers, each layer containing a vector path filled with a linear color gradient. We cast this problem as an optimization that jointly assigns each pixel to one or more layer and finds the gradient parameters of each layer that best reproduce the input. Since a trivial solution would consist in assigning each pixel to a different, opaque layer, we complement our objective with a simplicity term that favors decompositions made of few, semi-transparent layers. However, this formulation results in a complex combinatorial problem combining discrete unknowns (the pixel assignments) and continuous unknowns (the layer parameters). We propose a Monte Carlo Tree Search algorithm that efficiently explores this solution space by leveraging layering cues at image junctions. We demonstrate the effectiveness of our method by reverse-engineering existing cliparts and by creating original cliparts from studio photography (see Figure 2). This work was published at ACM SIGGRAPH ASIA and in ACM Transactions on Graphics 2017 [14].

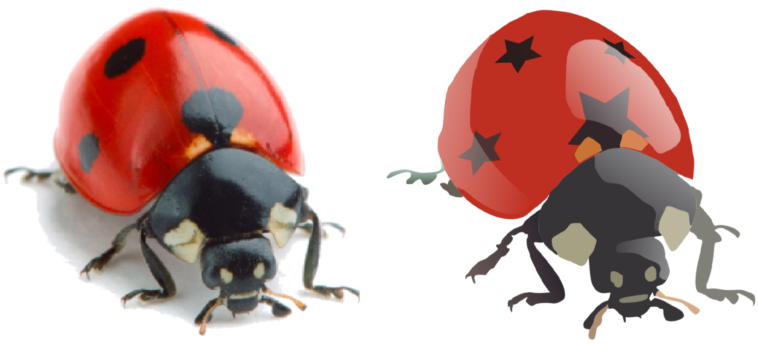

Figure 2. Photo2ClipArt. Our method generates an abstract, layered vector clipart, where each layer is filled with an opaque or semi-transparent linear color gradient. By expressing the input image (left) as a stack of linear color gradients, our vector graphics reproduce the visual style of traditional cliparts and are easy to edit. In the right example, we replaced the lady bug dots by little stars.

7.1.3. Semantic segmentation of 3D textured meshes

Participants: Florent Lafarge, Pierre Alliez.

In collaboration with Mohammad Rouhani, now at Technicolor, France.

Classifying 3D measurement data has become a core problem in photogrammetry and 3D computer vision, since the rise of modern multiview geometry techniques, combined with affordable range sensors. We introduce a Markov Random Field-based approach for segmenting textured meshes generated via multi-view stereo into urban classes of interest. The input mesh is first partitioned into small clusters, referred to as superfacets, from which geometric and photometric features are computed. A random forest is then trained to predict the class of each superfacet as well as its similarity with the neighboring superfacets. Similarity is used to assign the weights of the Markov Random Field pairwise-potential and accounts for contextual information between the classes. The experimental results illustrate the efficacy and accuracy of the proposed framework (See Figure 3). This work was published in the ISPRS journal [20].

7.1.4. Convolutional Neural Networks for Large-Scale Remote-Sensing Image Classification

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

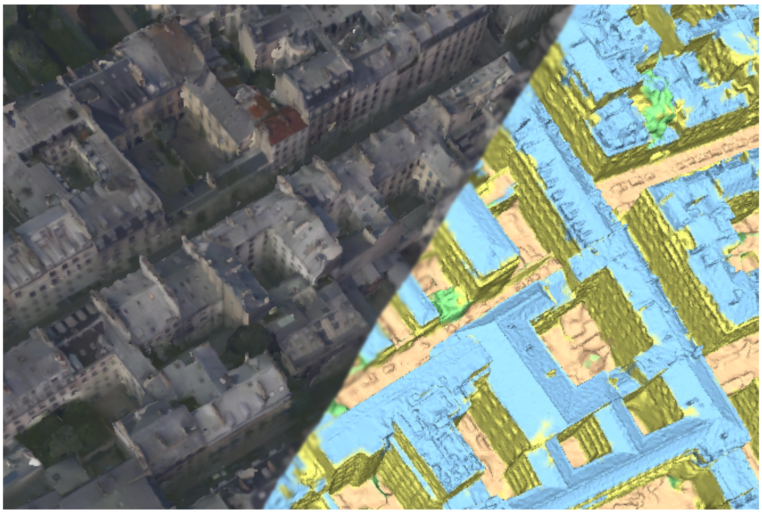

Figure 3. Semantic segmentation of 3D textured meshes. A textured mesh generated by Multiview stereo (left) is segmented into four urban classes of interest: building in blue, facade in yellow, ground in grey, and vegetation in green (right).

In collaboration with Guillaume Charpiat (Inria TAO team).

We propose an end-to-end framework for the dense, pixelwise classification of satellite imagery with convolutional neural networks (CNNs). In our framework, CNNs are directly trained to produce classification maps out of the input images. We first devise a *fully convolutional* architecture and demonstrate its relevance to the dense classification problem. We then address the issue of imperfect training data through a two-step training approach: CNNs are first initialized by using a large amount of possibly inaccurate reference data, then refined on a small amount of accurately labeled data. To complete our framework we design a multi-scale neuron module that alleviates the common trade-off between recognition and precise localization. A series of experiments show that our networks take into account a large amount of context to provide fine-grained classification maps (Figure 4). This work was published in IEEE Transactions on Geoscience and Remote Sensing (TGRS) [17].

7.1.5. High-Resolution Semantic Labeling with Convolutional Neural Networks

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

Convolutional neural networks (CNNs) were initially conceived for image categorization, i.e., the problem of assigning a semantic label to an entire input image. We have address the problem of dense semantic labeling, which consists in assigning a semantic label to *every* pixel in an image. Since this requires a high spatial accuracy to determine *where* labels are assigned, categorization CNNs, intended to be highly robust to local deformations, are not directly applicable. By adapting categorization networks, many semantic labeling CNNs have been recently proposed. Our first contribution is an in-depth analysis of these architectures. We establish the desired properties of an ideal semantic labeling CNN, and assess how those methods stand with regard to these properties. We observe that even though they provide competitive results, these CNNs often do not leverage properties of semantic labeling that could lead to more effective and efficient architectures. Out of these observations, we then derive a CNN framework specifically adapted to the semantic labeling problem [23], [18]. In addition to learning features at different resolutions, it learns how to combine these features

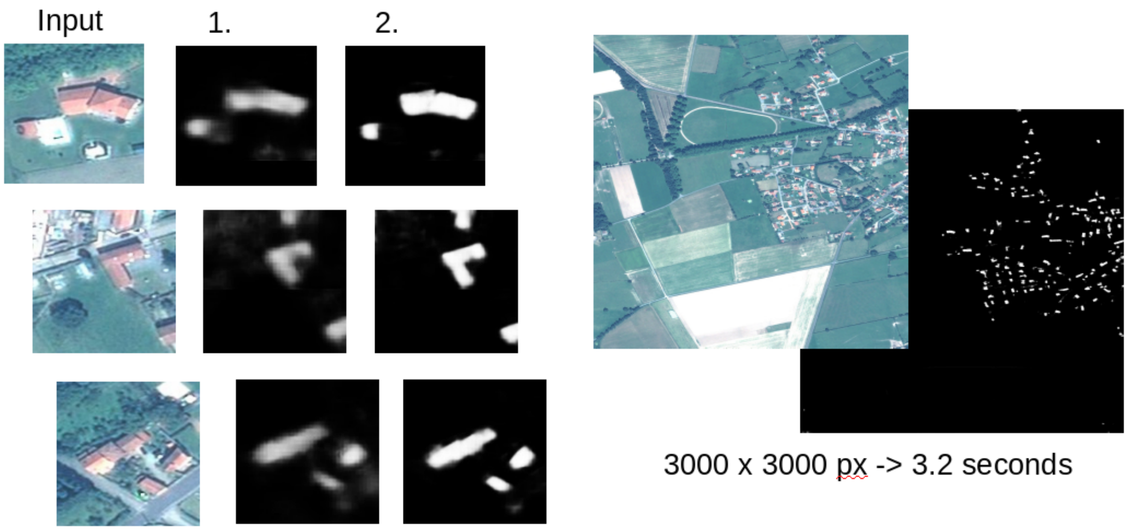

Figure 4. We train in a two-step scheme: first we train a fully convolutional network on large amounts of imperfect training data, to capture the generalities of the problem, which leads to coarse classification maps (1). In a second stage we fine-tune the network for few iterations on a precise manually labeled dataset, outputting fine classification maps as a results (2). The overall system is efficient and scalable.

(Figure 5). By integrating local and global information in an efficient and flexible manner, it outperforms previous techniques. We evaluate the proposed framework and compare it with state-of-the-art architectures on public benchmarks of high-resolution aerial image labeling. This work was published in IEEE Transactions on Geoscience and Remote Sensing and was presented at the IEEE International Geoscience and Remote Sensing Symposium (IGARSS).

7.1.6. Learning Iterative Processes with Recurrent Neural Networks to Correct Satellite Image Classification Maps

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

While initially devised for image categorization, convolutional neural networks (CNNs) are being increasingly used for the pixelwise semantic labeling of images. However, the proper nature of the most common CNN architectures makes them good at recognizing but poor at localizing objects precisely. This problem is magnified in the context of aerial and satellite image labeling, where a spatially fine object outlining is of paramount importance.

Different iterative enhancement algorithms have been presented in the literature to progressively improve the coarse CNN outputs, seeking to sharpen object boundaries around real image edges. However, one must carefully design, choose and tune such algorithms. Instead, our goal is to directly learn the iterative process itself. For this, we formulate a generic iterative enhancement process inspired from partial differential equations, and observe that it can be expressed as a recurrent neural network (RNN). Consequently, we train such a network from manually labeled data for our enhancement task. In a series of experiments we show that our RNN effectively learns an iterative process that significantly improves the quality of satellite image classification maps (Figure 6). This work was published in IEEE Transactions on Geoscience and Remote Sensing [16].

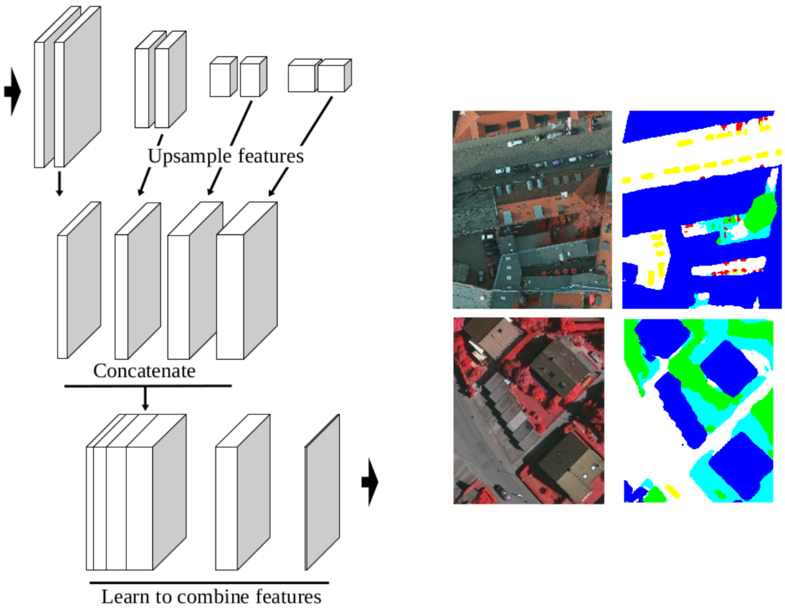

Figure 5. Our MLP network architecture (left) learns features at different resolutions and also learns how to combine those features. The technique was evaluated on the ISPRS 2D Semantic Segmentation Contest (right), providing competitive results.

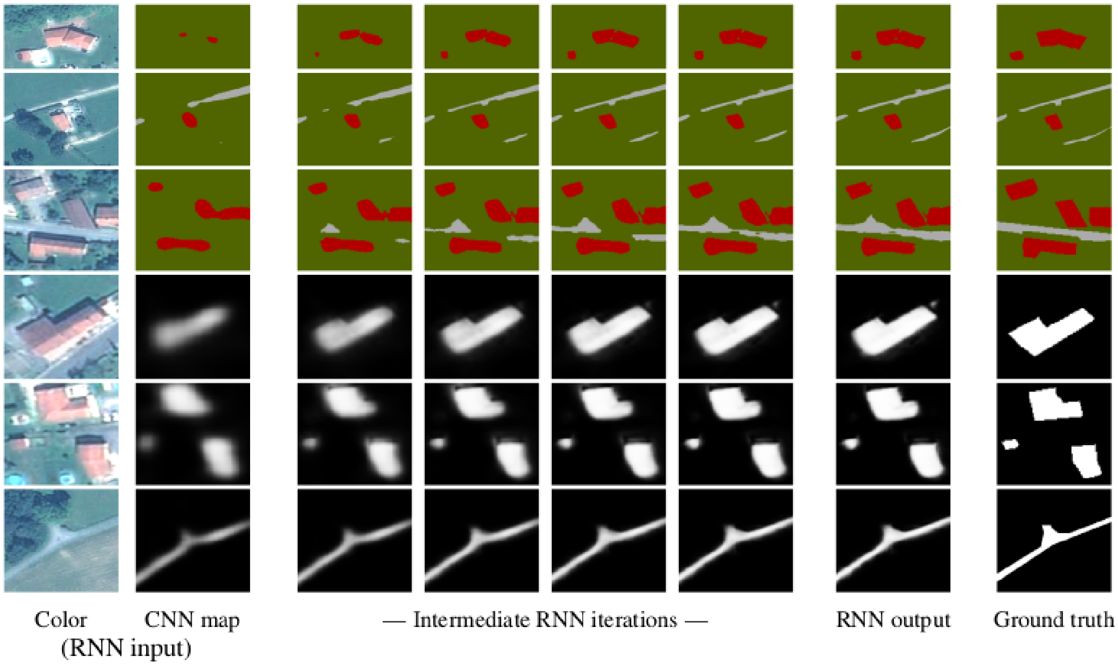

Figure 6. A recurrent neural network (RNN) learns an algorithm to iteratively correct the output of a coarse classification map. As a result, the satellite image classification maps become finer and better aligned to the real objects.

7.1.7. *Can semantic labeling methods generalize to any city? The Inria Aerial Image Labeling Benchmark*

Participants: Emmanuel Maggiori, Yuliya Tarabalka, Pierre Alliez.

In collaboration with Guillaume Charpiat (Inria TAO team)

New challenges in remote sensing impose the necessity of designing pixel classification methods that, once trained on a certain dataset, generalize to other areas of the earth. This may include regions where the appearance of the same type of objects is significantly different. In the literature it is common to use a single image and split it into training and test sets to train a classifier and assess its performance, respectively. However, this does not prove the generalization capabilities to other inputs. In this work, we propose an aerial image labeling dataset that covers a wide range of urban settlement appearances, from different geographic locations (see Fig. 7). Moreover, the cities included in the test set are different from those of the training set. We also experiment with convolutional neural networks on our dataset. This work was presented at the IEEE International Symposium on Geoscience and Remote Sensing (IGARSS) [22].

Figure 7. Close-ups of the dataset images and their corresponding reference data.

7.1.8. *Coarse to fine non-rigid registration: a chain of scale-specific neural networks for multimodal image alignment with application to remote sensing*

Participants: Armand Zampieri, Yuliya Tarabalka.

In collaboration with Guillaume Charpiat (Inria TAO team)

We tackle here the problem of multimodal image non-rigid registration, which is of prime importance in remote sensing and medical imaging. The difficulties encountered by classical registration approaches include feature design and slow optimization by gradient descent. By analyzing these methods, we note the significance of the notion of scale. We design easy-to-train, fully-convolutional neural networks able to learn scale-specific features. Once chained appropriately, they perform global registration in linear time, getting rid of gradient descent schemes by predicting directly the deformation. We show their performance in terms of quality and speed through various tasks of remote sensing multimodal image alignment. In particular, we are able to register correctly cadastral maps of buildings (see Fig. 8) as well as road polylines onto RGB images, and outperform current keypoint matching methods.

7.1.9. *Models for hyperspectral image analysis: from unmixing to object-based classification*

Participants: Emmanuel Maggiori, Yuliya Tarabalka.

In collaboration with Antonio Plaza (University of Extremadura)

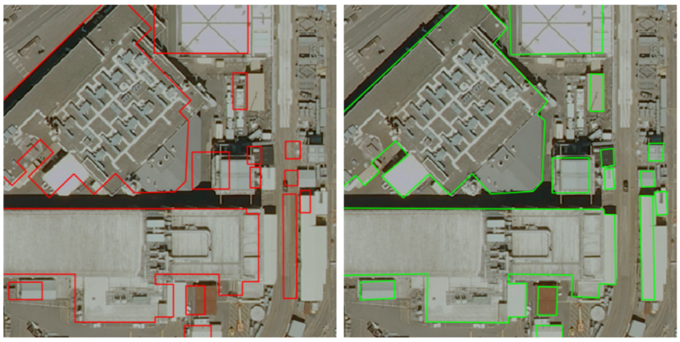

Figure 8. Example of image alignment with the proposed method. (Left) Original image and OpenStreetMap. (Right) Alignment result.

The recent advances in hyperspectral remote sensing technology allow the simultaneous acquisition of hundreds of spectral wavelengths for each image pixel. This rich spectral information of the hyperspectral data makes it possible to discriminate different physical substances, leading to a potentially more accurate classification (see example classifications Figure 9) and thus opening the door to numerous new applications. Throughout the history of remote sensing research, numerous methods for hyperspectral image analysis have been presented. Depending on the spatial resolution of the images, specific mathematical models must be designed to effectively analyze the imagery. Some of these models operate at a sub-pixel level, trying to decompose a mixed spectral signature into its pure constituents, while others operate at a pixel or even object level, seeking to assign unique labels to every pixel or object in the scene. The spectral mixing of the measurements and the high dimensionality of the data are some of the challenging features of hyperspectral imagery. This work presents an overview of unmixing and classification methods, intended to address these challenges for accurate hyperspectral data analysis. This work was published as a book chapter [26].

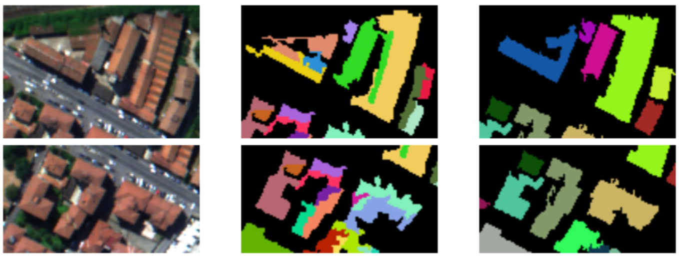

Figure 9. Example of building object-based classification using binary partition trees.

7.2. Approximation

7.2.1. Variance-Minimizing Transport Plans for Inter-surface Mapping

Participants: Pierre Alliez, Mathieu Desbrun.

In collaboration with Manish Mandad (former Ph.D. student) and Prof. Leif Kobbelt from RWTH Aachen, and with David Cohen-Steiner from the DataShape project-team.

We contribute an efficient computational method for generating dense and low distortion maps between two arbitrary surfaces of same genus [19]. Instead of relying on semantic correspondences or surface parameterization, we directly optimize a variance-minimizing transport plan between two input surfaces that defines an as-conformal-as-possible inter-surface map satisfying a user-prescribed bound on area distortion. The transport plan is computed via two alternating convex optimizations, and is shown to minimize a generalized Dirichlet energy of both the map and its inverse. Computational efficiency is achieved through a coarse-to-fine approach in diffusion geometry, with Sinkhorn iterations modified to enforce bounded area distortion. The resulting inter-surface mapping algorithm applies to arbitrary shapes robustly (figure 10), with little to no user interaction. This work has been published at the ACM SIGGRAPH conference.

Figure 10. Inter-surface mapping. Our approach generates a dense, low-distortion correspondence map between non-isometric surfaces through a geometrically-derived transport map minimizing local variances of associated neighborhoods. Only two user-defined constraints were prescribed in these models, at the tip of diametrically opposed limbs. Colors are used to indicate correspondences between all the models.

7.2.2. Error-Bounded and Feature Preserving Surface Remeshing with Minimal Angle Improvement

Participant: Pierre Alliez.

In collaboration with Kaimo Hu (former post-doc) and Bedrich Benes from Purdue University, with David Bommes from RWTH Aachen and Dong-Ming Yan from the National Laboratory of Pattern Recognition, Institute of Automation, Chinese Academy of Sciences.

Surface remeshing is a key component in many geometry processing applications. The typical goal consists in finding a mesh that is (1) geometrically faithful to the original geometry, (2) as coarse as possible to obtain a low-complexity representation and (3) free of bad elements that would hamper the desired application. Our remeshing algorithm [15] is designed to address all three optimization goals simultaneously by targeting prescribed bounds on approximation error, minimal interior angle and maximum mesh complexity. Our optimization framework applies carefully prioritized local operators in order to greedily search for the coarsest mesh with minimal interior angle and bounded approximation error. Fast runtime is enabled by a local approximation error estimation, while implicit feature preservation is obtained by specifically designed vertex relocation operators. Experiments show that our approach delivers high-quality meshes with implicitly preserved features and better balances between geometric fidelity, mesh complexity and element quality than the state-of-the-art (Figure 11). This work has been published in the IEEE Transactions on Visualization and Computer Graphics, and was presented at the EUROGRAPHICS Symposium on Geometry Processing.

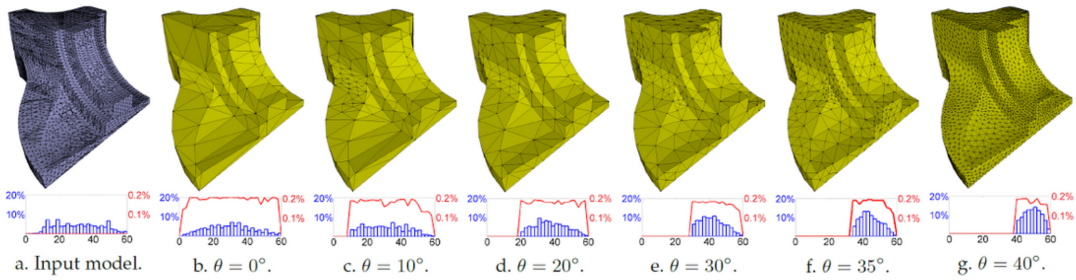

Figure 11. Examples of surface meshes generated with our approach. The input model (a) has 7.2k vertices. From (b) to (g) are the results with different minimal angle threshold. The blue histograms show the distribution of minimal angles of triangles and the red curves the corresponding approximation errors of these triangles. The error-bound threshold is set to 0.2% *of the diagonal length of the input's bounding box.*

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Google

Participants: Pierre Alliez, Cedric Portaneri.

We aim to develop a novel approach and software prototype for the compression of 3D models. Our main focus is on progressive compression of surface triangle meshes with color textures, with emphasis on fine grain, genericity and flexible metric. The proposed methodology is to turn the input models into a stream of refinements, in which both mesh and texture refinement details are multiplexed in accordance to rate-distortion principles. Fine grain will be achieved through considering all components, local as well as non-local, from both the mesh and its textures: mesh complexity, vertex accuracy, texture definition and accuracy. We will leverage the recent advances on perceptual metrics to improve the visual appearance, and perform joint consolidation and encoding of the models to further optimize the rate-distortion tradeoffs and visual perception.

- Starting date: January 2017 - Duration: 1 year

8.1.2. Geoimage

Participants: Liuyun Duan, Florent Lafarge.

The aim of this collaboration is to devise a new type of 2.5D representation from satellite multi-view stereo images which is more accurate, compact and meaningful than the conventional digital elevation models (DEMs). A key direction consists in incorporating semantic information directly during the image matching process. Such a semantic information is related to the type of components of the scene, such as vegetation, roofs, building edges, roads and land.

- Starting date: November 2013 - Duration: 4 years

8.1.3. CSTB

Participants: Hao Fang, Florent Lafarge.

The goal of this recent collaboration is to develop methods for analyzing and exploring scale-spaces into urban 3D data.

- Starting date: March 2016 - Duration: 3 years

8.1.4. Luxcarta

Participants: Jean-Philippe Bauchet, Florent Lafarge.

The goal of this recent collaboration is to design automated approaches for producing city models from the last generation of satellites. The models should conform to the level 2 (LOD2) of the popular CityGML format.

- Starting date: October 2016 - Duration: 3 years

8.1.5. CNES

Participants: Emmanuel Maggiori, Yuliya Tarabalka.

The objective of the project was to devise hierarchical approaches for object-oriented classification of multi-source images. Multi-source images are generated from a scene observed by different types of sensors.

- Starting date: November 2015 - Duration: 2 years

8.1.6. CNES and Acri-ST

Participants: Onur Tasar, Yuliya Tarabalka.

The aim is to devise efficient representations for satellite images.

- Starting date: October 2017 - Duration: 3 years

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9. Partnerships and Cooperations

9.1. National Initiatives

9.1.1. ANR

9.1.1.1. EPITOME: efficient representation to structure large-scale satellite images

Participants: Nicolas Girard, Yuliya Tarabalka [PI].

The goal of this young researcher project is to devise an efficient multi-scale vectorial representation, which would structure the content of large-scale satellite images.

- Starting date: October 2017 - Duration: 4 years

9.1.1.2. Faults_R_GEMS: Properties of FAULTS, a key to Realistic Generic Earthquake Modeling and hazard Simulation

Participants: Lionel Matteo, Yuliya Tarabalka.

The goal of the project is to study the properties of seismic faults, using advanced math tools including learning approaches. The project is in collaboration with Arizona State University, CALTECH, Ecole Centrale Paris, ENS Paris, ETH Zurich, Geosciences Montpellier, IFSTTAR, IPGP Paris, IRSN Fontenay-aux-Roses, LJAD Nice, UNAVCO Colorado and Pisa University.

- Starting date: October 2017 - Duration: 4 years

9.2. European Initiatives

9.2.1. FP7 & H2020 Projects

9.2.1.1. TITANIUM - Software Components for Robust Geometry Processing

Type: IDEAS

Instrument: ERC Proof of concept

Duration: 18 months

Coordinator: Pierre Alliez

Inria contact: Pierre Alliez

Abstract: The TITANIUM project aims to develop a software demonstrator for geometry processing and 3D urban modeling, in order to facilitate the pre-commercialization of novel software components for the Computational Geometry Algorithms Library. The demonstrator will include novel approaches resulting from the ERC-funded IRON project (Robust Geometry Processing, StG-2010-257474), which are illustrated by publications presented at premier conferences in our field and a patent submitted in 2015. The expected outcomes of TITANIUM will be versatile methods for 3D reconstruction and simplification of data gathered from geometric measurements, as well as related methods specifically tailored to urban modeling. These methods represent a significant step forward by offering unrivaled levels of robustness, and automated generation of levels of detail that are semantically meaningful. The acronym TITANIUM, a robust and lightweight material, conveys our wish to streamline the geometric modeling pipeline through robust algorithms and lightweight representations. This Proof of Concept project will also implement the steps required for pre-commercialization. In view of this goal, we have included an industrial partner, GeometryFactory, a spinoff from Inria. We have already established preliminary contacts in the fields of metrology and geographic information systems. These contacts will provide real-world industrial case studies.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Declared Inria International Partners

We collaborated with Mathieu Desbrun from Caltech, and Bedrich Benes from Purdue University.

9.4. International Research Visitors

9.4.1. Visits of International Scientists

- Mathieu Desbrun, Professor at Caltech, visited us from August to October.
- Gianmarco Cherchi, PhD student from University of Cagliary (Sardinia), visited us for three months (October-December) to collaborate on the refinement and optimization of polycubes.
- David Bommes, junior researcher from RWTH Aachen, visited us in September.

9.4.1.1. Internships

- Leman Feng (Ecole des ponts): Generation and optimization of high-order meshes. In collaboration with Laurent Busé and Hervé Delingette.
- Vinay Datta Renigunta (Hyderabad, India): Sinkorn iteration for optimal transport. In collaboration with David Cohen-Steiner.
- Armand Zampieri (Arts et Métiers Paristech): Aligning large-scale remote sensing images using neural networks.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Member of the Conference Program Committees

Pierre Alliez: ACM SIGGRAPH, EUROGRAPHICS, EUROGRAPHICS Star reports, EUROGRAPHICS Symposium on Geometry Processing, EG Workshop on Graphics and Cultural Heritage. He was an advisory board member for EUROGRAPHICS 2018 and chaired the EUROGRAPHICS 2017 Günter Enderle Award Committee.

Yuliya Tarabalka: IDAACS international conference.

10.1.1.2. Reviewer

- Yuliya Tarabalka was a reviewer for the journals IEEE PAMI, IEEE TIP, IEEE JSTARS, Remote Sensing.

10.1.2. Journal

10.1.2.1. Member of the Editorial Boards

Pierre Alliez is an associate editor of Computer-Aided Geometric Design and Graphical Models. He stepped down from ACM Transactions on Graphics in 2017. He is also a member of the editorial board of the CGAL open source project.

Florent Lafarge is an associate editor of The Visual Computer since 2015.

Yuliya Tarabalka is an associate editor for the Springer journal Sensing and Imaging and the International Journal of Computing since 2017.

10.1.2.2. Reviewer - Reviewing Activities

- Yuliya Tarabalka was a reviewer for the IEEE IGARSS conference (student competition selection committee).

10.1.3. Invited Talks

Florent Lafarge gave an invited talk at the Brazilian Symposium on Remote Sensing (SBSR 2017) at Santos, Brazil.

Yuliya Tarabalka gave an invited talk at the Brazilian Congress of Cartography at Rio de Janeiro, Brazil, and a tutorial on machine learning at IGARSS conference in Fort Worth, USA.

Pierre Alliez gave an invited seminar at collège de France (Géométrie algorithmique: Données, Modèles, Programmes).

10.1.4. Leadership within the Scientific Community

Pierre Alliez is a member of the Steering Committees of the EUROGRAPHICS Symposium on Geometry Processing and of the EUROGRAPHICS Workshop on Graphics and Cultural Heritage. He was also elected Executive Board Member for the Solid Modeling Association, for 4 years.

10.1.5. Scientific Expertise

Pierre Alliez reviewed two H2020 projects for the European commission. He was also a reviewer for the Belgium Fund for Scientific Research (FNRS).

Yuliya Tarabalka was an expert evaluator for Kazakhstan national research funding foundation, and she is a member of the expert panel SBWT (signal processing) of the FWO (Belgian research funding foundation) since November 2016.

10.1.6. Research Administration

Pierre Alliez: member of the BCP (bureau du CP) since 2015, comité MASTIC (popularization), and comité espace immersif.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master: Pierre Alliez and Florent Lafarge, Ingeniérie 3D, 21h, M2, university Nice Sophia Antipolis, France.
Master: Pierre Alliez and Florent Lafarge, 3D Meshes and Applications, 32h, M2, Ecole des Ponts ParisTech, France.
Master: Florent Lafarge, Traitement d'images numériques, 6h, M2, university Nice Sophia Antipolis, France.
Master: Pierre Alliez and Florent Lafarge, Mathématiques pour la géométrie, 30h, M1, EFREI, France.
Master: Pierre Alliez and Florent Lafarge, Curves and surfaces, 60h, M1, university Nice Sophia Antipolis, France.
Master: Pierre Alliez, Geometric modeling and processing, 15h, M2, Telecom SudParis, France.
Master: Yuliya Tarabalka, Discrete inference and learning, 12h, M2 MVA, ENS Paris-Saclay & CentraleSupelec, France.
Master: Yuliya Tarabalka, Mathematical methods,25h, MSc in data sciences and business analytics ESSEC-CS, CentraleSupelec, France.
Licence: Yuliya Tarabalka, Discrete optimization, 18h, L2, CentraleSupelec, France.
Licence: Yuliya Tarabalka, Advanced algorithms, 28.5h, L2 Networks and Telecoms, IUT Nice Côte d'Azur, France.

10.2.2. Supervision

PhD defended April 21st: Dorothy Duan, Semantized Elevation Maps, since October 2013, Florent Lafarge.
PhD defended June 22nd: Emmanuel Maggiori, Learning Approaches for Large-Scale Remote Sensing Image Classification, since January 2015, Yuliya Tarabalka and Pierre Alliez.
PhD in progress: Jean-Dominique Favreau, Sketch-based modeling in multi-view context, since October 2014, Florent Lafarge and Adrien Bousseau.
PhD in progress: Hao Fang, Scale-space understanding in urban scenes, since March 2016, Florent Lafarge.
PhD in progress: Jean-Philippe Bauchet, City modelling from high resolution satellite images, since October 2016, Florent Lafarge.
PhD in progress: Lionel Matteo: From Pleiades images to very high resolution topography in complex zones, since September 2017, Yuliya Tarabalka and Isabelle Manighetti.
PhD in progress: Onur Tasar, Using deep learning approaches to devise an efficient representation for large-scale satellite images, since October 2017, Yuliya Tarabalka and Pierre Alliez.
PhD in progress: Nicolas Girard, How to structure satellite data, since November 2017, Yuliya Tarabalka.

10.2.3. Juries

Pierre Alliez:

- Thesis reviewer: Giorgio Marcias (CNR Pisa, Italy).
- Thesis reviewer: Claudio Calabrese (University Roma, Italy).
- Thesis reviewer: Florian Caillaud (LIRIS Lyon).
- Thesis reviewer: Dmitry Anisimov (University Lugano).
- Thesis reviewer: Yannick Masson (University Paris Est).
- Thesis reviewer: Ana Vintescu (Telecom ParisTech).
- HDR committee president: Maks Ovsjanikov (Ecole Polytechnique).

Florent Lafarge:

- Thesis reviewer: Andras Bodis-Szomoru (ETH Zurich).
- Thesis examiner: Renato Martins (University Mines ParisTech).
- Thesis examiner:Rodrigo Ortiz Cayon (University Nice Sophia Antipolis).

Yuliya Tarabalka:

- Thesis examiner: Amine Bohi (University of Toulon).

10.3. Popularization

Pierre Alliez gave two seminars at CIV (olympic internship in mathematics) and for the national olympiads in geosciences (IESO).

11. Bibliography

Major publications by the team in recent years

[1] D. Bommes, M. Campen, H.-C. Ebke, P. Alliez, L. Kobbelt. *Integer-Grid Maps for Reliable Quad Meshing*, in "ACM Transactions on Graphics", July 2013, vol. 32, n^o 4, https://hal.inria.fr/hal-00862648

[2] L. Duan, F. Lafarge. *Towards large-scale city reconstruction from satellites*, in "European Conference on Computer Vision (ECCV)", Amsterdam, Netherlands, October 2016, https://hal.inria.fr/hal-01352466

[3] J.-D. Favreau, F. Lafarge, A. B. Bousseau. *Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients*, in "ACM Transactions on Graphics", 2017, vol. 36, n^o 6, https://hal.inria.fr/hal-01581981

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[10] Y. VERDIE, F. LAFARGE. *Detecting parametric objects in large scenes by Monte Carlo sampling*, in "International Journal of Computer Vision", January 2014, vol. 106, n° 1, pp. 57-75 [*DOI :* 10.1007/s11263-013-0641-0], https://hal.inria.fr/hal-00843022

Publications of the year

Doctoral Dissertations and Habilitation Theses

[11] L. DUAN. *Geometric modeling of urban scenes from satellite imagery*, Université Côte d'Azur, Apr 2017

[12] E. MAGGIORI. *Learning approaches for large-scale remote sensing image classification*, Université Côte d'Azur, June 2017, https://hal.inria.fr/tel-01589661

[13] Y. TARABALKA. *Learning Approaches for Remote Sensing Image Classification*, UCA, Inria, November 2017, Habilitation à diriger des recherches, https://hal.archives-ouvertes.fr/tel-01660895

Articles in International Peer-Reviewed Journals

[14] J.-D. FAVREAU, F. LAFARGE, A. B. BOUSSEAU. *Photo2ClipArt: Image Abstraction and Vectorization Using Layered Linear Gradients*, in "ACM Transactions on Graphics", 2017, vol. 36, n° 6, https://hal.inria.fr/hal-01581981

[15] K. HU, D.-M. YAN, D. BOMMES, P. ALLIEZ, B. BENES. *Error-Bounded and Feature Preserving Surface Remeshing with Minimal Angle Improvement*, in "IEEE Transactions on Visualization and Computer Graphics", January 2017 [*DOI :* 10.1109/TVCG.2016.2632720], https://hal.inria.fr/hal-01549584

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International Conferences with Proceedings

[22] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ. *Can Semantic Labeling Methods Generalize to Any City? The Inria Aerial Image Labeling Benchmark*, in "IEEE International Symposium on Geoscience and Remote Sensing (IGARSS)", Fort Worth, United States, July 2017, https://hal.inria.fr/hal-01468452

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[24] E. MAGGIORI, Y. TARABALKA, G. CHARPIAT, P. ALLIEZ. *Polygonization of Remote Sensing Classification Maps by Mesh Approximation*, in "ICIP 2017 - IEEE International Conference on Image Processing", Beijing, China, September 2017, 5 p. , https://hal.inria.fr/hal-01530460

Scientific Books (or Scientific Book chapters)

[25] PARTHENOS (editor). *Digital 3D Objects in Art and Humanities: challenges of creation, interoperability and preservation. White paper: A result of the PARTHENOS Workshop held in Bordeaux at Maison des Sciences de l'Homme d'Aquitaine and at Archeovision Lab. (France), November 30th - December 2nd, 2016*, PARTHENOS, Bordeaux, France, May 2017, 71 p. , https://hal.inria.fr/hal-01526713

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