ERC Starting Grant
Research proposal (Part B2)

Section 2: ***The Project proposal***

IRON: Robust Geometry Processing

Summary. *Digital Geometry Processing (DGP) started nearly ten years ago on the premises that geometry would soon become the fourth type of digital medium after sounds, images, and video. While recent research efforts have successfully established some theoretical and algorithmic foundations to deal with this very special ``signal'' that is geometry, DGP has not resulted in the expected societal and technological impacts that Digital Signal Processing has generated. We propose a focused research agenda to harness the full potential of digital geometry processing and make it as robust and impactful as digital signal processing. Specifically, the goal is to streamline the geometry processing pipeline, which cannot be achieved by simple adaptation of existing machinery. Instead, a whole new research phase is required to address such fundamental issues as reconstruction and approximation of complex shapes through ironclad techniques that are robust to defect-laden inputs and that offer strong guarantees on the outputs. Only then can DGP will be ready, as promised, to bring forth a technological revolution.*

a. State-of-the-art and Objectives

Digital geometry processing is a fast growing scientific field seeking to develop novel, automated methods to deal with the ever-increasing variety and abundance of geometric data. After the success of the three first waves of the digital multimedia revolution (sound, images and videos), the grand challenge for geometry processing is to elaborate the theoretical and algorithmic foundations for the acquisition, manipulation, transmission and manufacturing of complex 3D objects. For a vast array of applications ranging from multimedia to engineering through computer–aided medicine, ***geometry is the core of a digital model***: shape is the first and foremost attribute of a 3D object.

The main geometry processing tasks can be classified according to their end goal: a computerized shape representation can be used to visualize (creating a realistic or artistic depiction), simulate (anticipating the real) or realize (manufacturing a conceptual or engineering design). Aside from the mere editing of geometry, central research themes in geometry processing 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 rapid prototyping or machining.

Data

Geometric data are most commonly generated by modeling, by measurements or through automated processes. The abundance of data is explained by the recent, considerable advances in the modeling paradigms, in the acquisition technologies, and in the variety of automatic conversion methods. In addition, the numerous algorithms along the geometry processing pipeline themselves generate new, processed geometric data.

Measurement data range from point sets to depth images and contours. They are acquired with an increasing variety of acquisition technologies, whose evolution is characterized by a shift from contact to contact-free sensors, and from short to long range sensing culminating with satellite images. In many cases the acquired data are "raw" in the sense of being sparse, irregularly sampled, and riddled with uncertainty (noise and outliers). Therefore, and despite the expectation that technological advances should improve quality, geometric *datasets are instead increasingly unfit to direct processing*. This trend is explained by drastic change of scale in geometric datasets: projects

such as Google earth, geophysical measurements, or climate analysis involve measurements from satellite images or seismologic sensors—all of which containing a significant number of outliers.
In addition, geometric data are *increasingly heterogeneous* due to the combination of distinct acquisition systems, each of them acquiring a certain type of feature and level of details. Examples include the measurement of digital cities from satellites, planes and pedestrians. Data are thus not only heterogeneous, but may also be redundant. Albeit beneficial from the sampling point of view, redundancy hampers data registration. Further, we are observing a trend brought on by the speed of technological progress: while many practitioners use high–end acquisition systems, an increasing number of them turn to consumer–level acquisition devices such as digital cameras, hoping to replace an accurate but expensive acquisition by a series of low-cost acquisitions. Another evolution consists of dealing with *community data*: acquisition of our physical world can be achieved by exploiting the massive data sets available online, such as photo collections [1].

Automatically generated data appear throughout the geometry processing pipeline every time a conversion occurs or the geometry is altered. Example generated data are surface meshes generated by meshing parametric surfaces from CAD models. As the input data and the meshing algorithms are imperfect the output meshes may contain spurious defects such as gaps and self-intersections. This type of raw meshes, referred to as “polygon soups”, may severely hamper the robustness of geometry processing algorithms. In general processed data are riddled with imperfections due to the lack of guarantees provided by algorithms used along the processing pipeline. Ironically, many algorithms do not even guarantee for their output the very properties they require of their input. Since geometric data are increasingly heterogeneous as mentioned above, they require more conversions and processing, and are thus even more prone to contain flaws.

Methods

A major research effort in geometry processing in recent years has been to elaborate theoretical foundations and algorithms for analyzing and processing complex shapes through so-called discrete differential geometric operators. Significant theoretical and numerical advances have been made to prove that these operators mimic their smooth counterpart when applied to discrete computerized representations of 3D shapes. The main results are discrete equivalents of basic notions and methods of differential geometry [2], such as curvature and shape fairing of polyhedral surfaces.

Another important research direction has been to elaborate upon methods for converting shapes from one representation to another. In particular, the issue of shape acquisition and reconstruction has stimulated a considerable number of contributions already since the 80’s. In a recent survey we have listed more than 500 publications on this topic, revealing the lack of unified solution. More specifically, it took 15 years to elaborate a provably correct reconstruction approach based on Voronoi filtering [3] together with the first ingredients of a sampling theory for smooth shapes of arbitrary topology [4,5]. As these foundations are valid only for input measurement data which are both dense enough and noise free, they are of little practical use for the practitioners that increasingly have to deal with raw data (see Data section above). Consequently, a series of heuristics was devised to deal with noisy data sets. For example, no well-principled approach can altogether deal with piecewise-smooth reconstruction, outliers and heterogeneous inputs.
Similarly, the fundamental problem of shape approximation has been tackled through a variety of approaches such as mesh simplification [7,8], mesh refinement [4] and resurfacing through quadrangle surface tiling as needed in reverse engineering. Among these approaches, only a few can prove several guarantees of the output, e.g., in terms of topology and geometry [4,5]. The latter advances have been possible only through the introduction of novel theoretical concepts such as restricted Delaunay triangulations and epsilon-sampling. Furthermore, the reliability of the corresponding implementations has been possible only through an additional significant theoretical effort whose main result is the so-called *exact geometric computing* paradigm now commonly used for reliable geometric computing [6]. Finally, it is worth noting that most work in shape conversion

address the case of surfaces while the problem of hexahedron tiling of 3D domains is of increasing importance in computational engineering.

DGP vs. DSP

Over the past ten years I have been lucky to participate and contribute to the first wave of work in the field of digital geometry processing (DGP). The initial grand promise of DGP was to achieve what had been done in digital signal processing (DSP) but for the very special "signals" that shapes represent, with highly distinctive properties such as topology, dimensionality, and lack of global parameterization bringing a wealth of challenges. In many ways, DGP has been extremely successful in the sense that a wide variety of methods and algorithms have been developed to offer a vast array of geometry editing tools. However, digital geometry processing still has to provide the type of *robustness* to which digital signal processing owes its success: to be truly impactful at the scientific, technological and societal levels, DGP must offer a set of robust and reliable methods (as currently available for sounds or images) to practitioners. The level of robustness sought after (resilience to uncertainty and tolerance to heterogeneous data) constitutes an enduring scientific challenge, even more difficult than for ordinary signals due to the variety of geometric data. While creative and exploratory, the resulting algorithms of the first wave of DGP research are too brittle and input-dependent to offer solid foundations for technological advances. **The tenet of this proposal is that the potential of geometry processing techniques is far from being reached**. To fully realize its potential, one must tenaciously address the most enduring and fundamental problems hampering robustness to imperfect and heterogeneous input. I now elaborate on the most pressing issues we wish to address in this consolidation phase of DGP.

Dire Needs

Need for robustness: The vast majority of geometry processing methods work only for idealized, defect-free input data such as point sets without outliers, or intersection–free 2–manifold surface triangle meshes—not raw polygon soups. For instance, a great deal of work has been dedicated to the robustness of the discrete differential operators over triangle surface meshes: most operators now behave well even for meshes which are non uniform, irregular, and with small amount of noise. Many surface reconstruction algorithms from point sets many are also fairly robust to sparse sampling and noise. But considerably fewer algorithms are robust to highly non-uniform sampling and outliers (approximately one publication out of 50 deals with outliers). Similarly, almost none of the mesh processing algorithms of the "standard geometry processing toolbox" are robust to polygon soups, and mesh repair [9] is not a final solution. Robustness to defect-laden inputs is a largely unaddressed scientific challenge, and we argue that there is a need for a unified theory and algorithms capable of dealing with these data hampered with a variety of imperfections.

Need for genericity: The vast majority of current geometry processing methods work only for homogenous input data sets. For example, most algorithms are specialized to point sets, triangle meshes, or contours. When we need to deal with heterogeneous data or with new data types, the current solution consists of converting them to a common representation or to devise yet another specialized method. As each conversion adds some inaccuracy to the process and possibly some defects as well, this solution can be even more challenging to non-robust algorithms. Instead of requesting the practitioner to systematically convert everything, there is a need for a unified way of dealing with heterogeneous data.

Need for guarantees: The majority of geometry processing algorithms do not provide guarantees for their outputs, most likely because many target applications in computer graphics care about visual impact more than practical guarantees. For instance, over 300 references deal with surface mesh simplification [7], while only a few describe an algorithm which guarantees a global approximation tolerance error [8,10]. Even more surprisingly, none of these academic contributions can guarantee both a global tolerance error and an intersection–free output. This is all the more regrettable as the latter property is a strong requirement of many algorithms downstream the processing pipeline in computational engineering. Computational geometers, however, have always considered guarantees a priority. Alas, the theoretical assumptions on the input data are often not met in practical applications. For example, the provably correct Delaunay-based surface reconstruction algorithms [3] assume an epsilon sampling (i.e., dense enough and isotropic). Other algorithms provide some guarantees without unattainable assumptions, but do not fully address the problem. One concrete example is the Delaunay-based mesh refinement algorithm [4] which guarantees intersection-free and geometric error tolerances, but generates isotropic meshes that are unnecessarily complex.

Need for automation: The geometry processing pipeline ranges from acquisition to machining, including registration, reconstruction, repair, simplification, analysis, editing, watermarking, storage, transmission, searching and browsing. The lack of robustness, genericity, and guarantees we mentioned above makes the *streamlining of the whole processing pipeline* quite impossible; while each building block along the pipeline is presented as a fully automatic process in academic papers, their requirements for inputs and lack of guarantees of outputs prevents these building blocks from working together seamlessly. Practitioners thus need to deal with a trial-and-error iterative process, non conducive to efficient geometry processing. This lack of automation can have dire consequences for the computational engineer. For instance, an aircraft manufacturer may need to perform computational fluid dynamics simulation of production-level CAD model of a plane, which will have to be converted into a surface mesh which is watertight and intersection-free. Unnecessary features (such as interior details) may also need to be removed from the CAD model before being converted to a smooth surface mesh amenable to computations. The overall procedure involving conversion, repair and defeaturing currently takes weeks for an experienced engineer, while the simulation takes one hour of parallel computation on a cluster of 2K computers. As this procedure must be repeated for each major editing of the CAD model, and as it is the *wall clock time of a process that matters* in such industrial applications, it is of crucial important to reduce through automation its duration from weeks to hours. Similarly, removing the user from the loop is recognized as the critical issue when reconstructing digital models from measurements.

Objectives

My distinctive position of researcher involved into CGAL and industrial courses provides me with an acute knowledge on the most enduring problems reported by the practitioners and on the evolutions in terms of data and problems in the applications. This proposal builds upon the conviction that these problems cannot be solved solely through incremental improvements of the current methods and technology: the multiple challenges required to consolidating and further advancing DGP deserve five years of frontier research.

Specifically, I propose a problem-centric research program (as opposed to methodology-centric) which focuses on the central problems of *robust shape reconstruction and approximation*, covering the cases of surfaces, volumes and time-varying shapes. These problems, analog of measuring and converting signals in DSP, are chosen because they span the whole geometry processing pipeline and because they are the ones that hamper the most robustness and genericity to heterogeneous data. The terms reconstruction and approximation are intentionally intermingled to reveal the main chosen paradigm. Reconstruction herein covers registration, inference and super-resolution. Approximation herein covers shape and domain approximation with simplicial meshes as well as with quadrangle and hexahedron tilings. The three main challenges of the IRON proposal reflect their transversal nature as ranging from theory to algorithms and applications.

The IRON Challenges: Designing robust methods for geometry processing

C1 - Theory. Establish a theoretical framework for robust reconstruction and approximation

C2 - Algorithms. Design algorithms which are both robust and reliable, with strong guarantees

C3 - Applications. Demonstrate applicability and impact in computational engineering

b. Methodology

The key idea behind the methodology of this research project consists in handling the problems of reconstruction and approximation not separately, but in a joined manner: *thinking about the reconstruction problem as a scale-dependent approximation problem* (and vice-versa) will offer both the genericity and the ironclad robustness sought after. In essence this methodology proposes a shift in the way the problems are approached, offering reformulations that lead to well-posed, computationally tractable problems with sometimes substantially simpler solutions.

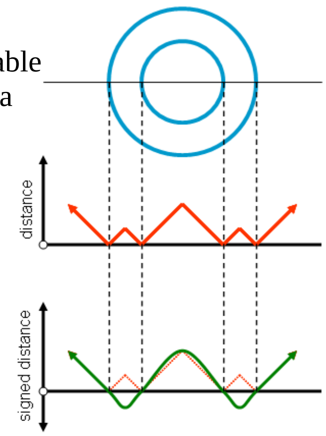
Streamlining the geometry processing pipeline can only be achieved by tackling the most enduring problems in geometry processing: robustness, genericity and guarantees. As the devil is always in the details, the methodology we propose in order to solve these open problems is far from being a single magic bullet, but instead a number of principled paradigms (as five years represent a long time frame for this quite new scientific field, we expect that these paradigms will evolve as other issues appear during the course of project):

- Robustness is commonly tackled through data denoising and outlier removal before processing, robust statistics, or explicitly constructed scale spaces. The proposal departs from these traditional approaches by resorting to integral computations and, in some cases, by raising the dimension of the problem. This translates into *integral, variational formulations*. Further, I propose to leverage recent advances in persistence theory to capture the most salient (persistent) features across scales, where the scale itself increases with the measure of the integration domain. The main choice is to not construct an explicit scale space through altering the data but instead to scale the integration domain. Furthermore, the integral formulation can take values into domains derived from robust geometric notions such as outlier-proof distance functions.
- Regarding genericity to heterogeneous data, the current dogma consists in choosing the data structure which is best suited to the queries required by the algorithms in hand. Turning the problem around, I propose instead to *adapt the queries to the geometric data*, and isolate a minimal set of so-called oracles required by the algorithms. As these oracles are the only interface through which the input geometry is known (or sensed), the algorithm becomes independent from the representation of the input geometry: genericity is gained and heterogeneous data can be handled gracefully.
- To offer guarantees for the output of algorithms, the conventional wisdom is to resort to explicit checking (and subsequent invalidation of) the elementary operations of a greedy algorithm, or performing the theoretical analysis of its execution flow. Instead, I propose to favor *constructive guarantees* where methods are designed to ensure properties by construction. This translates into, e.g., data structures which are intersection-free by construction when dealing with geometric problems requiring proper embedding, or into solving variational problems in a space of functions that have the properties sought after. In addition, one key concern of this proposal is to design algorithms which are amenable to computationally tractable algorithms. One of the main contentions of this proposal is that it is more reliable and efficient to process many simple primitives than a few complex ones. Embracing this concept, I propose to favor simplicial data structures (possibly in higher dimension) and weak formulations which are converging in the integral sense: this tends to drastically minimize the amount of computations. Finally, for the algorithmic aspects which involve basic data structures and geometric computing operations we will leverage existing technology in exact geometric computing available in CGAL library. Incidentally, the CGAL library was initially funded by a EU project before becoming an open source project.

I now provide more concrete details on how our methodology will be applied on three central and interrelated problems of geometry processing: reconstruction, approximation and tiling of geometric shapes. We describe our approach to each of these core problems, detailing the research parts expected to unravel quickly and outlining the high-risk/high-impact parts. The level of details go decreasing as the work package are sorted in chronological order and range from promising to adventurous research directions.

WP1 - Reconstruction

Assuming a geometric dataset made out of points or slices, the process of shape reconstruction amounts to recovering a surface or a solid matching these samples. This common 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. Reconstruction algorithms can also use an explicit set of prior shapes for inference [14], but this approach is generally unable to cover the expressive richness of all possible shape features in computational engineering. The concept of geometric simplicity has led to a number of interpolating techniques based upon the Delaunay triangulation, a canonical geometric partition based on the Euclidean distance between samples [5]. The concept of smoothness has led to a number of approximating techniques that typically compute an implicit function such as one of its isosurfaces is the inferred surface. Examples of such implicit functions are the approximate signed distance function to the inferred surface [15] or the indicator function to the inferred solid [13].



In recent years the "signed distance" approach has received considerable attention due to its robustness to noise, sparse sampling and missing data (as signing allows filling holes). However, this general method has several shortcomings: in addition to being in general not robust to outliers, it requires either having oriented normals in the input, or inferring the orientation of the normals. While recent attempts to automatically infer oriented normals from geometric datasets have been partially successful [12], normal orientation remains a brittle and ill-posed problem. Moreover, signed distances do not share the theoretical guarantees of robustness to noise and outliers that *unsigned* distance functions, based on optimal transport of positive measures, have recently offered [11]. For the **reconstruction of smooth shapes** I therefore propose to tackle the problem through fitting an implicit function which is obtained by *signing an outlier-proof unsigned distance function*. The novelty comes from the fact that instead of signing the input data before solving for the signed implicit function, we can instead rely on a robust unsigned distance function before signing it through a global (thus also robust) variational formulation. A key benefit of such variational signing is the fact that the signed version of a distance function can be made substantially smoother than its unsigned counterpart: the inset depicts a 2D shape composed of two nested circles (blue) and its unsigned distance function (red) measured along a horizontal line. Note how the red curve "bounces" off the zero distance axis in a non-smooth manner; the green curve depicts a signed and smoothed version of the red curve. We can take advantage of this 1D observation of *improved smoothness through signing* to devise a robust variational formulation able to fill up holes in the dataset. More specifically, the variational signing formulation amounts to turn, through an energy extremization process, a positive function f into another function g which is smooth and whose absolute value best matches f. Figure 1 depicts an example where the notion of smoothness herein is formalized as a polyharmonic energy. A look at the unsigned distance function (middle) reveals its robustness to outliers, as well as its inability to reconstruct a closed shape. An integral variational formulation to distance signing offers a robust way to induce a signed distance function that, by construction, will also fill holes gracefully.

A non-linear way to sign the positive function f is to solve for a function $\lambda(x)=+/-1$ such that $g(x)=\lambda(x)f(x)$ is as smooth as possible in the H^1 or H^2 sense. Alas, a non-linear solver generally hampers scalability: it is thus desirable to explore other solutions. We note that if we can provide the solver with an estimate of the sign of f (i.e., an inside/outside estimate $\lambda^*(x)$ of the inferred solid; see Figure 2), we can now use a simpler linear solver to minimize (in g) the energy $E = S(g(x)) + c(x)(f(x)-\lambda^*(x)f(x))^2$, where S is a (bi)harmonic energy term, and $c(x)$ is the local confidence in the guess λ^* (we removed the integral signs for clarity).

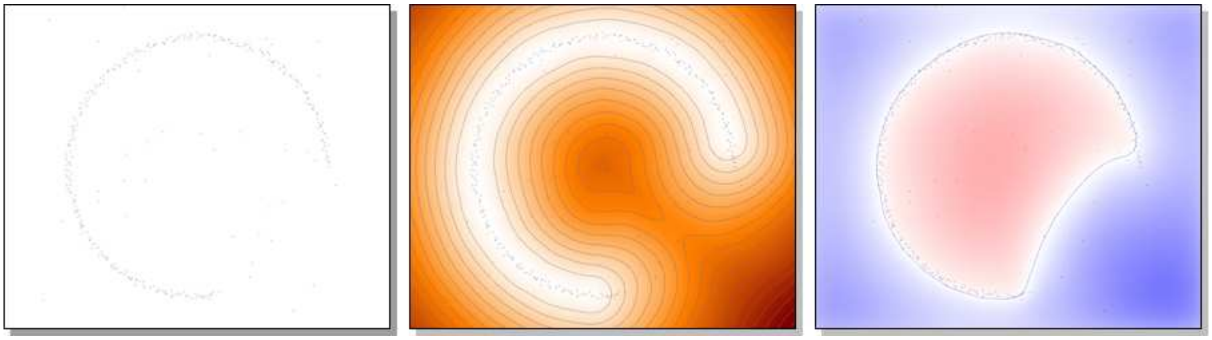


Figure 1. Reconstruction through signing of an outlier-proof distance function. Left: input point set with noise and outliers. Middle: visualization of the distance function robust to noise and outliers [7], “almost good” except for its sign and the hole due to sparse sampling. Right: signed distance function: the hole is now filled.

At this point one may think that we are back to the ill-posed “data orientation” problem as described above but it is not the case for the following reasons: i) the signed guess f* can be provided to the solver in a dense manner (i.e., at any point in the domain) while the oriented normals are provided only at input points. The robustness is this way substantially improved; ii) the confidence is another complementary information, equally important and provided densely as well; iii) the solver is robust to wrong signed guess contrary to, e.g., the Poisson reconstruction method [13] which can create one spurious connected component for each wrongly oriented normal. One possible direction to guess the sign (inside vs outside) at a given point p consists of shooting rays and counting the number of connected components where the robust unsigned distance function take low values. Combining this procedure with robust statistics would provide us with the sign and its confidence.

Beside the fact that we can rely on theoretically founded robust distance functions, the crux of this variational signing approach lies into the fact that we process functions which are not only dense but also inherently multi-scale. More specifically, in the noise free case a distance function can be constructed from the boundary of union of balls centered at the input data. As these balls grow when the distance increases the distance function gets smoother and smoother, hence is amenable to efficient and robust solving through multi-scale numerical methods. In addition I intend to explore the possibility to *parsimoniously* represent and solve for unsigned distance functions up to a user-specified approximation error. This way we view the reconstruction problem as an approximation one. Note that although the distance is not well defined close to the input points for high level of noise, the proposed formulation hands it over to the smoothing term as the confidence of the signed guess drops rapidly there. In addition, the robust unsigned distance functions apply in theory to all types of geometric primitives. With additional work we will thus be able to reconstruct from, e.g., polygon soups or non-parallel contours. In fact the proposed framework uses notions which are general enough to envision several extensions. We can extend this approach to the reconstruction of smooth surfaces with boundaries as the initial unsigned function can be used as a mask to trim out the parts of the final reconstructed surface which are located beyond certain unsigned distance values. We can further extend all principles to higher dimensions such as to time-varying data sets. Finally, the idea of processing functions instead of data calls for applying it to the non-rigid registration of multiple scan data, as well as to the super-resolution reconstruction [16]. The latter topic poses many challenges such as robustly registering all data without over smoothing as we wish in final to upscale the level of details.

On the theoretical side, we wish to prove that the reconstruction is correct in terms of geometry and topology and that it exhibits resilience to defect-laden inputs. Resilience formally translates into stability theorems with respect to noise and outliers. Correctness of the reconstruction translates into convergence in geometry and topology of the reconstructed shape with respect to the inferred shape known through increasingly dense measurements. One additional difficulty for proving resides in the numerical signing procedure devised to fill the holes and to extract the final shape.

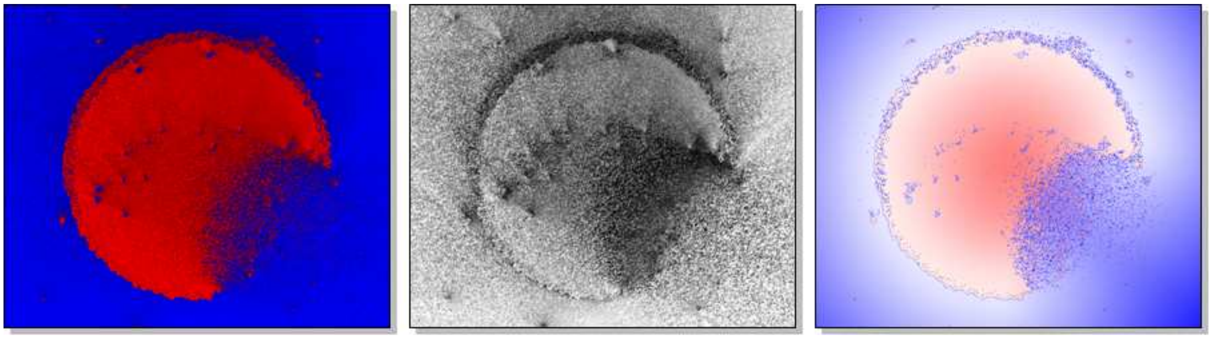


Figure 2. Estimating the sign and confidence of a signed distance function. Left: sign estimate (red vs blue) multiplied by confidence value. Middle: confidence value ranging between zero and one (black to white). Note how the confidence drops within the hole to be filled, inside the noise and in the vicinity of the outliers. Right: estimate of the signed distance function f^* obtained by multiplying the unsigned function by the sign estimate. In the color ramp used positive values range from white to red and negative values range from white to blue. The black curve delineates the zero level set (here very complex and noisy).

Moving from smooth to **piecewise smooth reconstruction** is considerably harder as the ill-posed aspect of the problem delineates to each dimension of the inferred features such as sharp crease and corners. In addition, a feature can span the whole model (see sharp creases on inset). All attempts to tweak the implicit function so as to make it piecewise smooth either do not provide a satisfactory solution or delegate the most enduring problem to the normal orientation and clustering step [18]. The low number of publications for the piecewise smooth case compared to the smooth case (1/30) reveals the difficulty of the problem. Further, very few approaches tackle the double issue of robustness (to noise and outliers) and feature reconstruction [19], and none to our knowledge addresses the latter issues from heterogeneous data (see left inset for a urban scene). The proposed solution consists of changing the view over the problem; and acknowledging the fact that a feature (e.g., a sharp crease) is a notion that exists only at some specific scales on measured data. Let us take the example of a whole city measured at increasingly detailed scales. A satisfactory reconstruction would produce a smooth terrain map at 100m resolution, shoe box building models with sharp creases at 1m resolution and smooth models at 1cm resolution. This says that the problem can not be decoupled from specifying an approximation scale. Pushing this idea further we propose to devise a method solely approximation-driven and inherently multi-scale. In addition, we believe that instead of tackling the task of recovering long range features (such as creases spanning large parts of a shape) it is better to attack the reconstruction problem throughout decreasing scales and *little by little* with simple probing atomic operations.

[too long] Favoring the “simplicity” assumption and discrete simplicial data structures for the sake of computational tractability, we propose to cast the piecewise smooth reconstruction problem as the one of refining a 3D simplicial complex represented as a Delaunay triangulation. This complex is used to drive the reconstruction across the scales without having to build an explicit scale-space model. Assume for the moment that we seek to reconstruct a piecewise smooth surface (not a solid) from a noise-free soup of triangles. At all time during refinement *all elements* of type vertex, edge and facet of the simplex act as probe emitters in order to query the input triangle soup. A vertex, respectively edge and face, emits its dual Voronoi cell, respectively face and edge as probe. Building upon the Delaunay refinement paradigm, this approach consists of inserting all elements into a single priority queue sorted by a surface approximation criterion. Each probe computes its intersection with the input triangle soup. For a Voronoi edge, respectively face and cell the intersection is either empty or generally a set of points, respectively segments and triangles. The so-computed intersections thus provide us with a set of Steiner vertices candidates for insertion into the complex. We retain the candidate Steiner vertex which provides the smallest local approximation error between the current approximation and the soup, and we use this error for sorting the priority queue. During refinement we repeatedly pop out of the queue the best element. If it is an edge this means that at the current scale (expressed here in approximation error) this edge wins over the other types of elements and its corresponding Steiner hypotheses that it is sitting on a sharp crease at the current probing scale. It remains to find how to consolidate these hypotheses across scales so as to recover the final reconstruction with its feature graph.

If we are now dealing with heterogeneous data hampered with noise and outliers (see inset for a urban scene), one direction consists of probing not the input primitives but their thickened versions where the corresponding offset function would be related to a robust distance function. We can vary the offset so as to consolidate the hypotheses that correspond to the most persistent across scales. The principle just presented is unified with the smooth case in the sense that it couples reconstruction and approximation. It is general in the sense that it works for heterogeneous data provided that we can query a robust distance function. Finally, we want to explore in a more adventurous research phase how it can be extended in higher dimensions for general stratified manifolds.

On the theoretical side we wish to prove that such approximation-driven reconstruction principle is both correct and resilient to defect laden data. Correctness relates to the proper reconstruction of topology and geometry under increasingly dense measurements, with the substantial complication that we must consider the topology of all components of the inferred stratified manifold. Specifically, a stratified manifold surface is a smooth embedded 2D manifold, except for a subset that consists of smooth embedded curves, except for a set of isolated points.

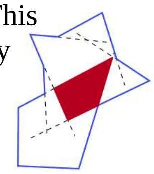
Smooth vs. Piecewise Smooth. At first glance it may seem impossible to unify the global variational formulation proposed for solving the smooth reconstruction problem, with the idea of refining little by little a simplicial complex for the piecewise smooth reconstruction problem. Nevertheless this is what we have in mind albeit the current idea is still very adventurous: consider the smooth reconstruction problem as *one* instance of a variational formulation. Such formulation requires defining a *domain* (and discretizing it when solving through a weak formulation). In the smooth case the domain is trivial and life is easy. For a stratified manifold we would like to reconstruct every sharp crease as a smooth curve, and every surface patch as the piece of a smooth surface. In other words this requires instantiating one variational formulation per curve and per surface patch with as many sub-domains. We are now left with the chicken-and-egg problem that we do not know the sub-domains as that is what we are looking for. Nevertheless there is light at the end of the tunnel if we reconsider the mesh refinement approach described above as our way to construct a discretization of the sub-domains, used as a scaffold to instantiate several variational formulations. It remains to explore how to couple these instances so that the smooth surface patches precisely meet at sharp creases and so that the smooth sharp creases meet at cusps and corners. Furthermore, we can imagine a methodology in tandem where all the variational instances guide across scales the domain refinement itself. After all, we know since the finite element methods that simplicial data structures (meshes) and variational formulations form a perfect alloy.

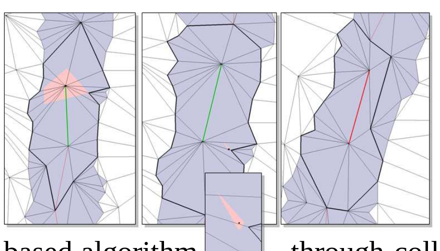
Online Reconstruction Benchmark. This work package comprises the development of an online reconstruction benchmark. There already exists two such benchmarks [21,22], but specialized to computer vision algorithms and outdoor scenes. They are extremely popular in computer vision research where reproducibility and evaluation of results are highly important. Based on my experience in coordinating the AIM@SHAPE repository (2M connections, 90K downloads since 2004), my goal is to rigorous establish a benchmark targeting researchers and practitioners. The first goal is to provide a high quality dataset in the form of digital models obtained through measurements with at least three distinct technologies. One key distinctive property of the datasets is that we will choose a set of 20 physical shapes which best cover the set of possible features at different scales (similar in spirit to image patterns with various contrasts and orientations). We will then ask a school of mechanical engineering to design and manufacture the corresponding physical shapes with certified accuracy. We will then scan the physical shapes and provide the registered measurement data online. The second goal is to elaborate upon a web service which measures accuracy and completeness of uploaded reconstructions against the ground truth (the native CAD model) which will *not* be distributed. The benchmark will compare not only the inter-surface distances, but also the inter-feature distances, the proportion of detected features and topology.

WP2 – Approximation

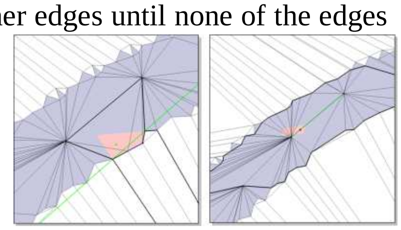
The shape approximation problem has received a considerable interest over the last few years, with various constraints depending on the final goal. Among the various proposed methodologies (refinement, simplification, clustering, optimization) the one which made the greatest impact for the practitioners is the greedy decimation of surface meshes through repeated application of the edge collapse operator. While many variants have been proposed (view-dependent, out of core, handling of attributes, etc) the variant of central interest here is the one which guarantees control over the global approximation error. Furthermore, we target several goals in addition to global error control: intersection free, resilience to heterogeneous data and robustness to noise and outliers. This includes being capable of repairing and simplifying altogether data such as triangle soup with cracks, self-intersections and gaps. In this context altering a decimation scheme so as to control through explicit checking the tolerance error and the self-intersections is clearly insufficient: the input data may already self-intersect and we can do more than just invalidating edge collapses.

The proposed direction to this problem consists of turning the problem around: instead of simplifying an input geometry inside a tolerance we *construct a tolerance volume around the input geometry, and degenerate it into a simplified surface triangle mesh*. This approach is motivated by mirroring the final argument in the proof of optimal linear interpolation of smooth functions with triangles: the locally optimal triangle element is the one whose anisotropy is related to the ratio between the two local principal curvatures of the function. Best herein simply means that for a given error tolerance, the triangle occupies the largest area in parameter space. In other words, setting the tolerance volume and maximizing the areas of the triangles within the tolerance (while covering the domain once) amounts to pursuing the same goal. The starting point is as follows: we first explicitly construct the tolerance volume by meshing it with a 3D simplicial mesh. This corresponds to the raise of dimension aforementioned, and presents the advantage of repairing, e.g., a polygon soup, provided that the tolerance is larger than the holes to be sealed. This provides us with an initial fine 3D mesh made of tetrahedra whose triangles are, by construction, intersection free. We then repeatedly simplify the 3D simplicial mesh through edge collapse operations. An edge is said collapsible when it maintains the intersection-free property. This condition is checked by first forming the 3D polyhedron from the union of the stars of the two edge vertices (all tetrahedra incident to the edge vertices) and by computing its *kernel* (see right inset) using, e.g., linear programming. If the kernel is non empty the edge can be safely collapsed when the merged vertex is located inside the kernel.





The left inset depicts in 2D the tolerance volume mesh in grey, a collapsible edge in green and its kernel in pink. A non-collapsible edge is depicted in red as its kernel is empty. Observe in the middle close-up how the kernel can be tiny albeit non-empty. This illustrates the power of the kernel which indicates the whole locus of points where placing the merged vertex. Finding the same tiny safe zone for a surface-based algorithm through collision detection would be an almost impossible task. If we now apply repeatedly the aforementioned edge collapses restricted to inner edges until none of the edges are collapsible we are left with long edges and high degree vertices inside the tolerance volume as shown in the right inset. Now observing that it is the boundary of the tolerance volume that impeaches further edge collapses, we can simplify the tolerance boundary itself, favoring the re-activation of collapsible inner edges. This is achieved by collapsing boundary edges in a conservative manner so that the tolerance volume is never increased. In practice it is sufficient to add the boundary itself as constraints in the linear program when solving for the polyhedron kernel

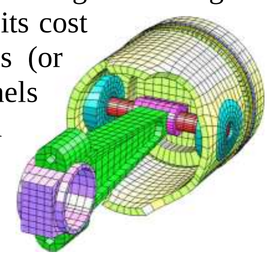


(pink in the right inset, left image). In the inset this operation reactivates the inner edge depicted in green. In passing simplifying the tolerance boundary tends to reduce the degree of the inner vertices, which itself favors non-empty kernels for the remaining inner edges. The overall idea consists of performing such operations for all edges of the tolerance volume until collapsing the tolerance volume itself into a surface, still in a conservative manner. This way the process terminates with zero tolerance while maintaining all guarantees throughout.

Although preliminary, the aforementioned direction for elaborating an algorithm is appealing in many aspects: all atomic operations are simple (hence tractable) and can be carried out reliably through existing linear programs. The tolerance volume itself can be constructed from either robust unsigned distance functions or signed distance functions (as discussed in WP1), for, e.g., filling the cracks of a polygon soup or simplifying topology excess. Furthermore we will explore an extension to the approximation of time-varying data as each component of such algorithm conceptually works in arbitrary dimensions. Nevertheless much research remains to understand i) what is the best order in which to apply the edge collapses; ii) where to pick the best location inside the kernels for the merged vertex; iii) how to depend as little as possible from the initial tessellation of the tolerance volume; and iv) if applying optimization to the tolerance mesh is relevant in order to stick even coarser meshes within the tolerance volume. Theoretically we want to show that the tolerance volume is always collapsible into a surface, and ideally that the complexity of the output mesh is within a small factor of the optimal. Finally, another adventurous part of this research consists of being able to use another error metric such as the other-way Hausdorff, the symmetric Hausdorff, or even a Sobolev norm which mixes geometry and normals. The latter may require a tolerance volume embedded in 6D, which poses a wealth of new challenges.

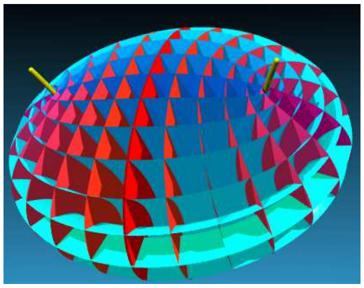
WP3 – Tiling

This work package covers the problem of quadrangle surface tiling and hexahedron domain tiling. Although we consider tiling as part of an approximation problem, we make a separate work package as the main goal encompasses by far the one of faithful approximation. The term tiling is employed instead of meshing to point out the fact that the tiles may be not just simple elements but can model complex smooth shapes such as parametric NURBS surface patches or parametric volume elements. 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 well the input (e.g., inside a tolerance volume and intersection-free) and such that each tile matches certain properties related to its shape or its size. Quadrangle tilings are also used for the manufacturing of panels in freeform architecture. Given the surface of a freeform digital model, the goal is to tile it with a set of panels such that their union approximates well the surface, their arrangement matches the aesthetic goal of the architect and their properties match a number of constraints related to manufacturing. Albeit non trivial to translate into geometric terms, the notion of aesthetic is often related to the regularity of connectivity and geometry of the global tiling. Beside feasibility, the manufacturing constraints consist essentially in reducing its cost through minimizing the number of molds needed to manufacture the panels (or equivalently, maximizing the number of similar panels) and favoring simpler panels (flat, then simply curved, then doubly curved panels). Hexahedron domain tilings (see inset) are used for simulation of physical phenomena such as computational fluid dynamics. They are more used in practice than tetrahedron meshes, although they are notoriously much harder to generate.



The automatic generation of quality quadrangle and hexahedron tiling is one of the most enduring problems in mesh generation. Many methods are for this reason only interactive or require post-processing. For hexahedron tiling most approaches proceed by deforming a Cartesian grid or an octree. Other approaches are based on whisker weaving, embedded Voronoi graphs or shelling.

As the tiling problem is global by nature we propose to tackle it through an integral, variational formulation. We intend to tackle the problems of quadrangle and hexahedron tiling in a unified manner by solving for three 3D scalar functions whose isosurfaces tile the input surface or 3D domain. More specifically, we will solve through a variational formulation a triply orthogonal system, which consists of three foliations of E^3 by surfaces that intersect orthogonally at each point.



The key idea to make such foliations data-dependent is to force, in the vicinity of the domain boundary, one of the foliated sheets to be parallel to the domain boundary. From Euler theorem the two other foliated sheets must coincide with the lines of curvatures of the domain boundary [22], a required property from the approximation point of view. As for the approximation problem we can couple reconstruction and tiling by querying the input 3D domain within a robust, signed distance function. One key difficulty consists of being able to deal with domain boundaries subtending sharp creases, as the solver must allow for automatic switching between the tangent foliated sheets at the creases. Contrary to the case of surface tiling such switching can not be modelled by solving in the space of angles modulo ninety degrees. At the theoretical level we must ensure that we can extract from the three triply orthogonal foliations a set of isosurfaces whose union tiles the input domain with only hexahedra and, e.g., no complex polyhedral cells due to saddle configurations. Further, it is required to control in addition to the shape of the tiles (obtained via the triply orthogonal property, see inset) all other application-dependent constraints such as regularity, size, approximation error, and easy of manufacturability. The methodology will be most probably in final much different from our previous methodology based on discrete harmonic one-forms. Although this topic is certainly the most adventurous part of this research program we plan to tackle all issues aforementioned, armed with our experience and past success on quadrangle surface tiling.

Expected Results and Impact

The main results of the new IRON team will mostly take the form of theory and algorithms for shifting the knowledge in robust geometry processing. Although the proposal is primarily problem-centric, we wish with the proposed paradigms to form during the course of the project the pieces of a larger puzzle geared toward establishing a unified framework with unprecedented levels of robustness. In addition, we propose to further deliver courses for young European students and researchers, as well as for industrial researchers and engineers in the field. Specifically, we intend to submit tutorials at conferences such as EUROGRAPHICS in SIGGRAPH, as well as to organize special sessions and mini-symposia. The rigorous reconstruction benchmark will be our way to animate the community around the open problem of robust piecewise smooth surface reconstruction. The main reconstruction and approximation algorithms will be implemented as new components for the CGAL library. Ultimately IRON wants to serve as the primary catalyst for excellent European research in the field.

The main objective of the proposed research program is to consolidate DGP and bring it to its full scientific and technological potential. Besides the algorithmic and theoretical contributions to geometry processing, the impact of our methodology will be significant in application areas where geometry acquisition and processing play a central role. These include computational and reverse engineering as well as manufacturing for freeform architecture. In the following we discuss the expected impacts with respect to each of the three main considered challenges:

- **C1 – Theory**: As mentioned earlier, algorithms which are robust to input and provide output guarantees are scarce in digital geometry processing. Through the proposed methodology we aim at developing a general framework with both solid algorithmic and theoretical properties. In particular, theoretical guarantees such as an ironclad robustness to noisy input should be applicable in practical settings, i.e., in situations where the level of noise is high or when the number of outliers is comparable to the number of inliers (e.g., a common occurrence in point sets generated from dense photogrammetry). Due to the generality of the proposed methodology, it is to be expected that our robust and generic methods be also used as crucial components of future developments in geometry processing.

- **C2 - Algorithms**: The methodological framework we propose will lead to reliable algorithms when combining it with existing robust geometric computing technology such as the tools available from the CGAL library. The methods that we plan to implement and diffuse through new components of CGAL will demonstrate the capabilities and robustness of the algorithms to both practitioners and researchers in the field. In addition, we plan to make the reconstruction algorithms available as web services accessible from the online reconstruction benchmark to further maximize the impact of our research contributions. For very large scale problems, we may require parallel or out-of-core implementations. We plan to further leverage the current research project by searching for additional funding to achieve this task.
- **C3 - Applications**: Building over previous experience in technology transfer, I am ideally positioned to efficiently convert the research results in technological components with high impact in industrial applications. A primary focus will be on making an impact for computational engineering. The latter is of increasingly crucial importance for the competitiveness of industries such as aircraft or car manufacturers. Computational engineering departs from traditional engineering by replacing physical prototypes and experiments by digital models and simulations. The role of the engineer remains the same (conceiving, anticipating the real), but the gain in effectiveness is considerable. As reported by many industrial contacts of mine (which include the leader in CAD software industry), the issue of converting production-level CAD models into defect-free meshes ready for simulation is recognized as the most labor-intensive part of the conception cycle by far (with a duration typically expressed in weeks of wall clock). The results of this proposal are likely to reduce this duration to hours instead of weeks, offering a giant leap towards the grand challenge of efficient iterations between simulation and modeling. Further, the automatic generation of quality hexahedron meshes for simulation will improve the effectiveness of the conception cycle. Overall this will translate into increased competitiveness of the European manufacturing industry. Finally, it is worth mentioning that computational engineering also applies to simulations of complex physical phenomena (thermal, fluids, electromagnetism) at the scales of entire cities for the grand environment challenge of conceiving safe and sustainable cities. Finally, after five years of research the results of this proposal will serve as a basis for the next step: technology. They will propel this new and much needed IT area forward, making it ready for hardware implementations.

Why ERC. The distinctive property of the ERC funding would provide the IRON research team with a unique opportunity to implement the proposed research agenda with a *critical mass* of young talented researchers, students and invited professors. As the IRON project would trigger the creation of a new European research team in the emerging field of digital geometry processing, part of the job will also be a human adventure focused around exciting research topics. Finally, and as a principal investigator, being able to invest the major part of my efforts into a single project focused on the most enduring topics would concretize the dream of carrying on a high risk/high impact research.

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c. Resources

Besides me as principal investigator, the team envisioned to work on this project will consist of one junior associate researcher for two years at the beginning of the project, one postdoctoral fellow for year two, three Ph.D. students (3 years each, spread throughout the duration of the project), and one research engineer who will assist us year two and three for implementing the reconstruction benchmark and the reconstruction algorithms as CGAL components. In addition we will seek for additional local funding in order to sponsor more engineering manpower and more interns. From year three we expect the hiring of an additional permanent researcher.

This project will constitute my main research effort (70%), with the remaining time dedicated to my participation to existing projects. As the principal investigator I will be in charge of the overall scientific direction and management of the project. I will also mentor the postdoctoral fellow and together with the junior associate researcher, we will supervise the Ph.D. students. The Ph.D. students will each work on the three main work packages of the project and additional help will be provided by my current Ph.D. student.

The research group will be part of [xxx] Moreover, I am in charge of a course on “3D Meshes and Applications” at the Ecole des Ponts ParisTech, one of the leading French school of engineering. I have prime access to excellent M.S. students. These students will be recruited first for their M.S. internships (“pre-docs”), then as Ph.D. students if there is a match with the listed objectives. The Ph.D. students will be dedicated to the following tasks:

- Ph.D. student #1 (year 1 to year 3): Robust shape reconstruction
- Ph.D. student #2 (year 2 to year 4): Robust shape approximation
- Ph.D. student #3 (year 3 to year 5): Hexahedral domain tiling for computational engineering

We summarize below the resources that we request to support the creation and growth of the IRON team, and allow to fulfil its ambitious goals:

- 3 Ph.D. students for three years each (total 325 KE)
- 1 postdoctoral fellow for one year (56 KE)
- 1 junior associate researcher for two years (total 142 KE)
- Invited professors: two times three months (total 18 KE)
- 1 research engineer for two years (144 KE)
- Travels (total 60 KE): participation to conferences and workshops (40 KE), participation to summer schools (10 KE) and meetings with research collaborators (10KE).
- Equipment (total 40 KE) distributed as follows: five computers delivered throughout the duration of the project (15 KE), two high-end computers to run the CGAL nightly test suites (15 KE) and one high-end server computer for the reconstruction benchmark (10 KE).
- Design and manufacturing of reference models for the online reconstruction benchmark (total 20 KE for 20 models). Design, manufacturing and metrology will be provided by a French school of engineering in mechanics.

	Cost Category	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Total (Y1-5)**
Direct Costs:	**Personnel**:						
	PI	**62 805**	**62 805**	**62 805**	**62 805**	**62 805**	**314 025**
	Associate researcher	**70 965**	**70 965**				**141 930**
	Post doc		**55 843**				**55 843**
	PhD grant 1	**35 595**	**35 595**	**35 595**			**106 785**
	PhD grant 2		**36 130**	**36 131**	**36 131**		**108 392**
	PhD grant 3			**36 671**	**36 672**	**36 672**	**110 015**
	Research engineer		**72025**	**72 026**			**144 051**
	Predoc grants	**11 563**	**11 563**				**23 126**
	Invited researchers	**8 832**	**8 833**				**17 665**
	Total Personnel:	**189 760**	**353 759**	**243 228**	**135 608**	**99 477**	**1 021 832**
	Other Direct Costs:						
	Equipment	**10 000**	**10 000**	**10 000**	**5 000**	**5 000**	**40 000**
	Travel	**10 000**	**15 000**	**15 000**	**10 000**	**10 000**	**60 000**
	Reference models for benchmarks		**20 000**				**20 000**
	Total Other Direct Costs:	**20 000**	**45 000**	**25 000**	**15 000**	**15 000**	**120 000**
	Total Direct Costs:	**209 760**	**398 759**	**268 228**	**150 608**	**114 477**	**1 141 832**
Indirect Costs (overheads):	max 20% of direct costs	**41 952**	**79 752**	**53 645**	**30 122**	**22 895**	**228 366**
Total Costs of project:	(by year and total)	**251 712**	**478 511**	**321 873**	**180 730**	**137 372**	**1 370 198**
Requested Grant:	(by year and total)	**251 712**	**478 511**	**321 873**	**180 730**	**137 372**	**1 370 198**

[max 15 pages here]

For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:	**70%**

d. Ethical Issues

	Research on Human Embryo/ Foetus	YES	NO
	Does the proposed research involve human Embryos?		
	Does the proposed research involve human Foetal Tissues/ Cells?		
	Does the proposed research involve human Embryonic Stem Cells (hESCs)?		
	Does the proposed research on human Embryonic Stem Cells involve cells in culture?		
	Does the proposed research on Human Embryonic Stem Cells involve the derivation of cells from Embryos?		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X
	Research on Humans	**YES**	**NO**
	Does the proposed research involve children?		
	Does the proposed research involve patients?		
	Does the proposed research involve persons not able to give consent?		
	Does the proposed research involve adult healthy volunteers?		
	Does the proposed research involve Human genetic material?		
	Does the proposed research involve Human biological samples?		
	Does the proposed research involve Human data collection?		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X
	Privacy	**YES**	**NO**
	Does the proposed research involve processing of genetic information or personal data (e.g. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?		
	Does the proposed research involve tracking the location or observation of people?		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X
	Research on Animals	**YES**	**NO**
	Does the proposed research involve research on animals?		
	Are those animals transgenic small laboratory animals?		
	Are those animals transgenic farm animals?		
	Are those animals non-human primates?		
	Are those animals cloned farm animals?		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X
	Research Involving Developing Countries	**YES**	**NO**
	Does the proposed research involve the use of local resources (genetic, animal, plant, etc)?		
	Is the proposed research of benefit to local communities (e.g. capacity building, access to healthcare, education, etc)?		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X
	Dual Use	**YES**	**NO**
	Research having direct military use		
	Research having the potential for terrorist abuse		
	DO ANY OF THE ABOVE ISSUES APPLY TO MY PROPOSAL?		X

Other Ethical Issues	YES	NO
Are there **OTHER** activities that may raise **Ethical Issues**?		X
If **YES** please specify:		

Section 3: *Research Environment* (max 2 pages)

a. Host institution

INRIA is the host institution for this proposal. This project will be physically hosted by the INRIA Sophia Antipolis - Méditerranée. INRIA, the national institute for research in computer science and control, operates under the dual authority of the Ministry of Research and the Ministry of Industry. It is dedicated to fundamental and applied research in information and communication science and technology (ICST). The Institute also plays a major role in technology transfer by fostering training through research, diffusion of scientific and technical information, development, as well as providing expert advice and participating in international programs. By playing a leading role in the scientific community in the field and being in close contact with industry, INRIA is a leading participant in the development of ICST in France. Throughout its eight research centres in Rocquencourt, Rennes, Sophia Antipolis, Grenoble, Nancy, Bordeaux, Lille and Saclay, INRIA has a workforce of 3,700, 2,900 of whom are scientists from INRIA and INRIA partner organizations such as CNRS (the French National Center for Scientific Research), universities and leading engineering schools. They work in 152 joint research project-teams. Many INRIA researchers are also professors whose approximately 1,000 doctoral students work on theses as part of INRIA research project-teams. INRIA has an annual budget of 162ME, 20% of which comes from its own research and technology transfer contracts.

INRIA has the distinctive property of being organized in “project-teams” of moderate sizes, whose members share common goals, without any intermediate structures such as departments. I am currently part of the GEOMETRICA project-team (http://www-sop.inria.fr/geometrica/), which is specialized in computational geometry and topology. Upon funding, the ERC grant would allow me to create a new project-team devoted to geometry processing, one year after the start of the project.

b. Additional institutions (additional participants)

Transition to independence

My goal is to develop the ambitious research program described in this proposal. This research program requires starting a new team, and ERCs support is likely to have three beneficial effects for reaching the critical size, by:

- providing sufficient resources to start the research project, and create my own project-team after the first year of the start of the project, as agreed with INRIA;
- thanks to the high visibility of ERC, strengthening the team by attracting talented researchers from Europe or elsewhere in the world;
- in a wider perspective, allowing the team to participate to the stimulating top level research community that will emerge from the ERC.

Intellectual Support and Collaboration

My research environment is particularly rich and helpful in achieving the objectives of this proposal. INRIA is a world-class research institute with leading researchers in computer science (JD Boissonnat, …). I can also benefit from the support of the current GEOMETRICA team members (J.-D. Boissonnat, D. Cohen-Steiner, M. Yvinec, F. Chazal) and visiting professors (M. Desbrun, L. Kobbelt). I have a long-lasting collaboration with Prof. Desbrun from Caltech [] For the targeted applications [A. Lieutier, Dassault Systems].