IN PARTNERSHIP WITH:
Université de Lorraine

Activity Report 2019

Project-Team MFX

Matter From Graphics

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

RESEARCH CENTER
Nancy - Grand Est

THEME
Interaction and visualization

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Project-Team MFX

Creation of the Project-Team: 2019 November 01

Keywords:

Computer Science and Digital Science:

A5.5.1. - Geometrical modeling
A5.5.2. - Rendering
A8.3. - Geometry, Topology

Other Research Topics and Application Domains:

B5.7. - 3D printing

1. Team, Visitors, External Collaborators

Research Scientists

Sylvain Lefebvre [Team leader, Inria, Senior Researcher, HDR]
Samuel Hornus [Inria, Researcher]
Jonàs Martínez Bayona [Inria, Researcher]

Faculty Member

Cédric Zanni [Univ de Lorraine, Associate Professor]

PhD Students

Melike Aydinlilar [Univ de Lorraine, from Nov 2019]
Semyon Efremov [Inria]
Jimmy Étienne [CNRS]
Thibault Tricard [Univ de Lorraine]

Technical staff

Jean Baptiste Austruy [Univ de Lorraine, Engineer, from May 2019]
Pierre Bedell [Inria, Engineer]
Pierre-Alexandre Hugron [Univ de Lorraine, Engineer, from Apr 2019]
Yamil Salim Perchy [Inria, Engineer]
Noémie Vennin [Univ de Lorraine, Engineer, until Jun 2019]

Interns and Apprentices

Adrien Bedel [Inria, from Sep 2019]
Anas El Moussaoui [Univ de Lorraine, from Jul 2019 until Sep 2019]
Adrien Tétar [Inria, until Jun 2019]

2. Overall Objectives

2.1. Overall Objectives

Digital fabrication has had a profound impact on most industries. It allows complex products to be modeled in Computer Assisted Design (CAD) software, and then sent to Computer Aided Manufacturing (CAM) devices that physically produce the products. Typical CAM devices are computer controlled lathes and milling machines that are ubiquitous in mass-production chains, along with injection molding and assembly robots. The design of a new product requires a large pool of expertise consisting of highly skilled engineers and technicians at all stages: design, CAD modeling, fabrication and assembly chains.

Within CAM technologies, the advent of additive manufacturing (AM) (i.e., 3D printing) together with powerful and inexpensive computational resources let us envision a different scenario. In particular, these technologies excel where traditional approaches find their limitations:

- Parts with complex geometry can be fabricated in a single production run and the cost has no direct relation with the geometric complexity.
- The cost-per-unit for fabricating an object is constant and significantly lower than that of producing a small series of objects with traditional means. Though it is not competitive on a mass production scale where the cost-per-unit decreases as the number of produced units increases.
- The machine setup is largely independent of the object being fabricated, and thus these technologies can be made available through generic 3D printing companies and online print services. Additionally, the machines are significantly easier to operate than traditional fabrication means to the extent of making them accessible to the general public.

As a consequence, it becomes possible to design and produce parts with short development cycles: physical objects are uniquely and efficiently fabricated from digital models. Each object can be personalized for a specific use or customer. The core difficulty in this context lies in modeling parts, and this remains a major obstacle as functional and manufacturability constraints have to be enforced. By *functional* constraint we refer here to some desired behavior in terms of rigidity, weight, balance, porosity, or other physical properties. This is especially important as AM allows the fabrication of extremely complex shapes, the scales of which vary from a few microns to a few meters. All this moves AM well beyond traditional means of production and enables the concept of *metamaterials*; materials where parameterized microstructures change the behavior of a base shape fabricated from a single material.

Exploiting this capability turns the modeling difficulties into acute challenges. With such a quantity of details modeling becomes intractable and specifying the geometry with standard tools becomes a daunting task, even for experts. In addition, these details have to interact in subtle and specific ways to achieve the final functionality (*e.g.*, flexibility, porosity) while enforcing fabrication constraints. On the process planning side (i.e, the set of computations turning the part into printing instructions), large parts filled with microstructures, porosities and intricate multi-scale details quickly lead to huge data-sets and numerical issues.

Our overall objective is to develop novel approaches enabling experts and practitioners alike to fully exploit the advantages of AM. We aim to achieve this by developing novel algorithms that automatically synthesize or complete designs with functional details. We consider the full chain, from modeling to geometry processing onto the optimization of 3D printer instructions.

3. Research Program

3.1. Research Program

We focus on the computational aspects of shape modeling and processing for digital fabrication: dealing with shape complexity, revisiting design and customization of existing parts in view of the novel possibilities afforded by AM, and providing a stronger integration between modeling and the capabilities of the target processes.
We tackle on the following challenges:

- develop **novel shape synthesis and shape completion algorithms** that can help users model shapes with features in the scale of microns to meters, while following functional, structural, geometric and fabrication requirements;
- propose methodologies to help *expert* designers **describe shapes** and designs that can later be **customized and adapted** to different use cases;

- develop novel algorithms to **adapt and prepare complex designs** for fabrication in a given technology, including the possibility to modify aspects of the design while preserving its functionality;
- develop novel techniques to **unlock the full potential of fabrication processes**, improving their versatility in terms of feasible shapes as well as their capabilities in terms of accuracy and quality of deposition;
- develop **novel shape representations, data-structures, visualization and interaction techniques** to support the integration of our approaches into a single, unified software framework that covers the full chain from modeling to printing instructions;
- **integrate novel capabilities** enabled by advances in additive manufacturing processes and materials **in the modeling and processing chains**, in particular regarding the use of functional materials (*e.g.* piezoelectric, conductive, shrinkable).

Our approach is to cast a holistic view on the aforementioned challenges, by considering modeling and fabrication as a single, unified process. Thus, the modeling techniques we seek to develop will take into account the geometric constraints imposed by the manufacturing processes (minimal thickness, overhang angles, trapped material) as well as the desired object functionality (rigidity, porosity). To allow for the modeling of complex shapes, and to adapt the same initial design to different technologies, we propose to develop techniques that can automatically synthesize functional details within parts. At the same time, we will explore ways to increase the versatility of the manufacturing processes, through algorithms that are capable of exploiting additional degrees of freedom (*e.g.*, curved layering [21]), can introduce new capabilities (*e.g.*, material mixing [22]) and improve part accuracy (*e.g.*, adaptive slicing [20]).

Our research program is organized along three main research directions. The first one focuses on the automatic synthesis of shapes with intricate multi-scale geometries, that conform to the constraints of additive manufacturing technologies. The second direction considers geometric and algorithmic techniques for the actual fabrication of the modeled object. We aim to further improve the capabilities of the manufacturing processes with novel deposition strategies. The third direction focuses on computational design algorithms to help model parts with gradient of properties, as well as to help customizing existing designs for their reuse.

These three research directions interact strongly, and cross-pollinate: *e.g.*, novel possibilities in manufacturing unlock novel possibilities in terms of shapes that can be synthesized. Stronger synthesis methods allow for further customization.

4. Application Domains

4.1. Digital Manufacturing

Our work addresses generic challenges related to fabrication and can thus be applied in a wide variety of contexts. Our aim is first and foremost to develop the algorithms that will allow various industrial sectors to benefit more strongly from the potential of AM. To enable this, we seek collaborations with key industry partners developing software and AM systems for a variety of processes and materials that are of interest to specific sectors (*e.g.*, dental, prosthetic, automotive, aerospace).

4.2. Medical Applications

To allow for faster transfer of our techniques and unlock novel applications, we actively seek to develop applications in the medical sector. In particular, we are involved in a project around the design of orthoses which explores how our research on elasticity control through microstructure geometries can be specifically applied to the medical sector; see §9.1.1.

5. Highlights of the Year

5.1. Highlights of the Year

This year we advanced on all of our main research axes [11], [12], [13], [14], [15], [17]. We would like to highlight two of these results. First, we cast a new view on the Gabor noise – a now well established procedural texturing technique – by reformulating it to enable new controls and properties [17]. This opens interesting possibilities for microstructure synthesis, a direction we are now pursuing. Second, we introduced a novel algorithm for curved 3D printing [11], a long term ongoing effort within the team. This algorithm is the first – to our knowledge – to optimize for curved layers throughout a part, under constraints allowing fabrication on standard 3D printers using thermoplastic filament. This paves the way to more general techniques for 6-DOF 3D printing.

Our software efforts have also intensified, with a clear increase in the use and popularity of our software IceSL (see *software*). We also announced an exciting collaboration with *AddUp*, a leading French company in the field of metal 3D printing.

6. New Software and Platforms

6.1. Chill

Chill, node-based graphical interface for IceSL

KEYWORDS: 3D - Additive manufacturing

SCIENTIFIC DESCRIPTION: ChiLL is an effort to explore visual modeling tools for IceSL. The core idea behind Chill is to propose a node-based modeling interface, which is a popular way to facilitate the design of 3D objects without going directly through code. Our approach creates a bridge between nodes-based editing and scripting, as the syntax for creating a new node is identical to the scripting language used in IceSL.

FUNCTIONAL DESCRIPTION: In Chill a user creates 3D shapes by connecting various nodes arranged in a directed graph. The shape visualization is updated instantly as the graph is modified.

NEWS OF THE YEAR: Chill was publicly released during the summer of 2019. We will broadly communicate about it in 2020.

- Participants: Jimmy Etienne, Pierre Bedell, Thibault Tricard, Yamil Salim Perchy and Sylvain Lefebvre
- Contact: Sylvain Lefebvre

6.2. IceSL

KEYWORD: Additive manufacturing

SCIENTIFIC DESCRIPTION: IceSL is the software developed within MFX, that serves as a research platform, a showcase of our research results, a test bed for comparisons and a vector of collaborations with both academic and industry partners. The software is freely available both as a desktop (Windows/Linux) and an online version.

FUNCTIONAL DESCRIPTION: IceSL allows users to model complex shapes through CSG boolean operations. Objects can be directly prepared and sent to a 3d printer for fabrication, without the need to compute an intermediate 3D mesh.

NEWS OF THE YEAR: In 2019, IceSL has been featured in news, exhibitions and fairs as a well-established tool for 3D printing. Additionally, since its inception, IceSL's community has grown significantly together with the number of new features included in it for slicing and modeling.

Regarding new features and additions to the software in 2019, IceSL has gone through many changes, primarily focused on improving the user experience and scalability/stability of algorithms. The most visible change is the complete rework of the slicing parameters GUI, with the addition of category-icons to allow for a quick access to settings. We can also note the upgrade of the renderer to support wide and high resolution screens, and the possibility to choose an experimental renderer (based on HCSG, published last year).

On the slicing front, we added new features, long requested, from the community: ironing, automatic spiralization, selection of different nozzle diameters, minimum time per layer, etc. A new GUI to customize the supports points was also added to help with the generation of supports.

The social community of IceSL has been growing steadily. Our twitter account has around 338 followers, 187 users frequently interacting in its Google forum (respectively, a progress of 69% and 25% since last year). Downloads have increased by 78% from last year (55K downloads total). In addition, Slicecrafter, the online version, has a cumulative of around 15K sliced objects.

- Participants: Frédéric Claux, Jean Hergel, Jérémie Dumas, Jonas Martinez-Bayona, Samuel Hornus, Sylvain Lefebvre, Pierre Bedell, Cédric Zanni, Noemie Vennin, Thibault Tricard, Jimmy Etienne, Yamil Salim Perchy and Pierre-Alexandre Hugron
- Contact: Sylvain Lefebvre
- URL: https://icesl.loria.fr

6.3. Platforms

Participants: Pierre Bedell, Noémie Vennin, Pierre-Alexandre Hugron.

We continued our active participation within the Creativ'Lab, a common experimental platform funded by Inria, Loria, CNRS and Région Grand Est. We added novel machines (DLP resin printers and large format printers) to explore new problems related to the specificity of each technology. We are also in the process of revisiting some of our techniques in the context of resin 3D printing.

This year we kept developing our custom-made hardware, in particular our color filament 3D printers. In this context we also elaborated our own colored PLA filament (using a filament extrusion device, PLA pellets and pigments). This was instrumental to the success of the corresponding research [15]. Finally, we started the assembly of a 3D printer based on a robotic arm, in the context of our research on curved 3D printing.

We are making these installations available to industrial partners and other research teams.

7. New Results

7.1. Star-shaped Metrics for Mechanical Metamaterial Design

Participants: Jonàs Martínez, Mélina Skouras, Christian Schumacher, Samuel Hornus, Sylvain Lefebvre, Bernhard Thomaszewski.

Digital manufacturing technologies such as 3D printing and laser cutting enable us to fabricate designs with great geometric detail. One particular way of exploiting this capability is to create patterned sheet materials whose geometric structures can be tailored to control their macro-mechanical behavior.

A typical approach to model and analyze structured sheet materials is centered around the concept of a representative element—a tile—which is repeated, transformed, and laid out so as to generate a regular spatial tiling. Changing the shape of the representative tile allows to control macro-mechanical properties such as isotropy or negative Poisson's ratios. Generalizing this material design principle from a single representative tile to *families* of tiles that can be combined in a spatially-varying manner opens the door to structures with progressively-graded material properties.

At SIGGRAPH 2019 we have presented a method for designing mechanical metamaterials [14]. It is based on the novel concept of Voronoi diagrams induced by star-shaped metrics. As one of its central advantages, our approach supports interpolation between arbitrary metrics (see Figure 1). This capability opens up a rich space of tile geometries with interesting aesthetics and a wide range of mechanical properties. They include isotropic, tetragonal, orthotropic, as well as smoothly graded materials. We have validated the mechanical properties predicted by simulation through tensile tests on a set of physical prototypes. An open source C++ implementation of the technique can be found at https://github.com/mfx-inria/starshaped2d

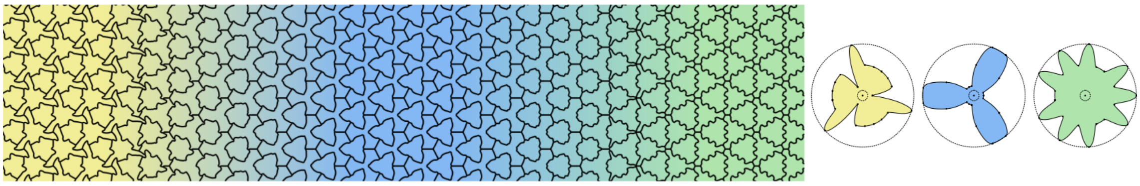


Figure 1. Our method generates a smoothly-graded pattern (left) when interpolating between three star-shaped distance functions (regular) on a regular honeycomb lattice. Each distance function is compactly parameterized with polar coordinates, allowing for simple interpolation in metric space as indicated by color-coding.

7.2. Anisotropic convolution surfaces

Participants: Alvaro Javier Fuentes Suárez, Evelyne Hubert, Cédric Zanni.

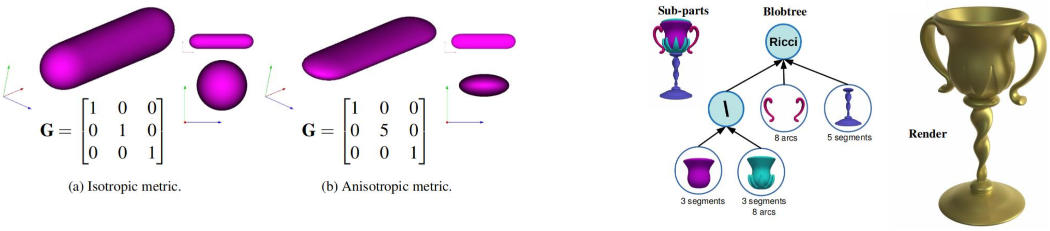
Skeletons, as a set of curves and/or surfaces centered inside a shape, provide a compact representation of the shape structure. Due to this property, skeletons have proved useful in many applications that range from shape analysis to 3D modeling and deformation. Convolution surfaces associate radii information to the skeleton and provide a simple way for users to rapidly define a shape. A convolution surface is an implicit surface defined as a level set of a scalar field, the convolution field, that is obtained by integrating a kernel function over the skeleton. This technique allows us to build a complex shape by modeling parts that combine into a smooth surface, independently of the smoothness of the skeleton itself. They also represent a volume with the convolution surface as its boundary and can therefore be combined with other composition operators from implicit modeling frameworks.

We have introduced anisotropic convolution surfaces [12], an extension that increases the modeling freedom by providing ellipse-like normal sections around 1D skeletons. It increases the diversity of shapes that can be generated from 1D skeletons, and reduces the need for 2D skeletons, while it still retains smoothness. We achieve anisotropy not just in the normal sections but also in the tangential direction. This allows sharper and steeper radius variation, and the control of thickness at skeleton endpoints (see Figure 2). The method is applied to skeletons represented by bi-arcs. It allows us to control precisely the orientation of anisotropy thanks to rotation minimizing frames. This work was presented at Shape Modeling International 2019.

7.3. Procedural Phasor Noise

Participants: Thibault Tricard, Semyon Efremov, Cédric Zanni, Fabrice Neyret, Jonàs Martínez, Sylvain Lefebvre.

Procedural pattern synthesis is a fundamental tool of Computer Graphics. In 2019 we introduced a new formulation that generates a wide range of patterns that could not be produced by other techniques. Our procedural *phasor noise* is based on a prior technique called Gabor noise, which creates oscillating patterns with accurate control over their frequency content (power spectrum). Gabor noise achieves this by summing a large number of Gabor kernels — Gaussian weighted sinewaves — distributed pseudo-randomly in space. Unfortunately Gabor noise suffers from local loss of contrast and lacks control over the shape of the oscillations (which always have a sinewave profile).



(a) Isotropic metric.

(b) Anisotropic metric.

Figure 2. Our method, based on an anisotropic metric, allows us to generate an ellipse-like cross section around 1D skeletons (segments, bi-arcs). The thickness around the skeleton can be controlled precisely both in the orthogonal cross-section and in the tangential direction giving finer control to the user. The density field generated can then be used in a classical implicit modeling framework.

Our method solves these limitations by reformulating Gabor noise to expose its instantaneous phase. Once the phase obtained we can directly remap a periodic profile function onto it, to obtain an oscillating pattern of constant contrast and controlled profile geometry, while retaining all desirable properties of Gabor noise (see Figure 3). This unlocks two main applications. The first is in texture synthesis for computer graphics, to generate color, displacement and normal fields. The second is in additive manufacturing, where our method can be applied in 3D to generate a wide range of microstructures.

This work was done in collaboration with Fabrice Neyret (MAVERICK, Inria) and has been published in ACM Transactions on Graphics, in 2019 [17]. Thibault Tricard and Semyon Efremov did a joint presentation at ACM SIGGRAPH 2019.

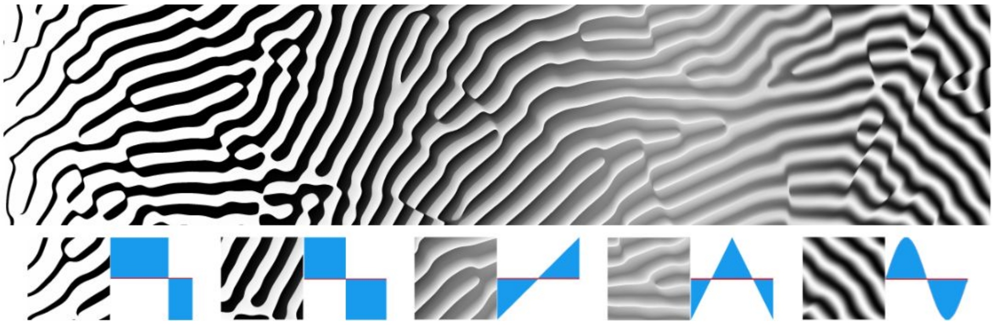


Figure 3. Phasor noise is a novel procedural function generating strongly oriented, coherent stripe patterns. The profiles of the oscillations are controlled (here: square, triangular, sine).

7.4. Ribbed support vaults for 3D printing of hollowed objects

Participants: Thibault Tricard, Frédéric Claux, Sylvain Lefebvre.

In additive manufacturing, and in particular with the popular filament-based fabrication, the printing time remains a major constraint. In a typical print, most of the time is spent filling the interior of the object. Based on this observation we explored how to print an object as empty as possible. The difficulty is that any deposited material has to be supported from below to prevent the object from collapsing.

We developed a simple, yet very efficient, algorithm that generates a lightweight ribbed support vault infill (see Figure 4). Our algorithm sweeps once through the slices from top to bottom, detects non-supported points, and connects them with a segment to the closest already supported points. The endpoints of open segments are eroded from one slice to the next. This process generates hierarchical ribbed support vaults that quickly retract and merge with the enclosing walls, while offering printability guarantees.

Our approach greatly reduces material usage (reaching parts as empty as 98%) and thus strongly reduces print time. Nevertheless it guarantees printability, and scales to very large inputs.

This work originated from the University of Limoges and was the master topic of Thibault Tricard, under the supervision of Frédéric Claux and in collaboration with Sylvain Lefebvre. The work was published in Computer Graphics Forum in June 2019 [16].

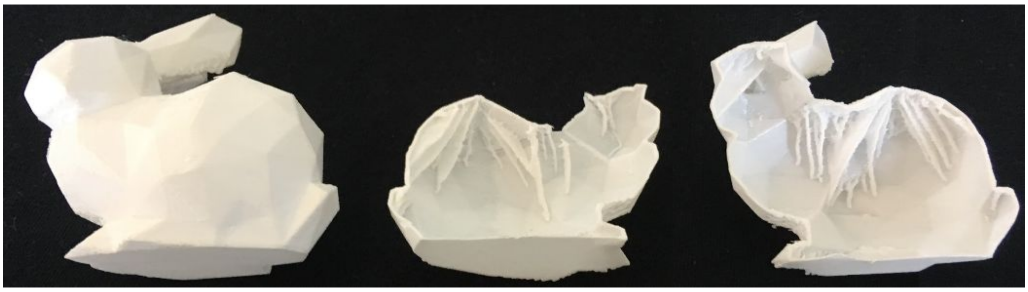


Figure 4. A 3D bunny model printed with our internal ribbed supports. It is mostly empty, with the ribbed vaults providing just enough support to prevent filament to fall during manufacturing.

7.5. CurviSlicer: Slightly curved slicing for 3-axis printers

Participants: Jimmy Étienne, Nicolas Ray, Daniele Panozzo, Samuel Hornus, Charlie C.l. Wang, Jonàs Martínez, Sara Mcmains, Marc Alexa, Brian Wyvill, Sylvain Lefebvre.

Most additive manufacturing processes fabricate objects by stacking planar layers of solidified material. As a result, produced parts exhibit a so-called staircase effect, which results from sampling slanted surfaces with parallel planes. Using thinner slices reduces this effect, but it always remains visible where layers almost align with the input surfaces. In this research we exploit the ability of some additive manufacturing processes to deposit material slightly out of plane to dramatically reduce these artifacts.

We focused in particular on the widespread Fused Filament Fabrication (FFF) technology, since most printers in this category can deposit along slightly curved paths, under deposition slope and thickness constraints. Our algorithm curves the layers, making them either follow the natural slope of the input surface or on the contrary, make them intersect the surfaces at a steeper angle thereby improving the sampling quality.

Rather than directly computing curved layers, our algorithm deforms the input model before slicing it with a standard planar approach. The deformation is optimized for reproduction accuracy. We demonstrate that this approach enables us to encode all fabrication constraints, including the guarantee of generating collision-free toolpaths, in a convex optimization that can be solved using a QP solver.

This work emerged from a problem solving session between its co-authors at the 17th international Bellairs Workshop on Computational Geometry (2018). It was then pursued during 2019 in the context of the PhD thesis of Jimmy Étienne and as a collaboration with Nicolas Ray (PIXEL, Inria). The work was published in ACM Transactions on Graphics in 2019 [11] and presented at ACM SIGGRAPH 2019 by Jimmy Étienne.

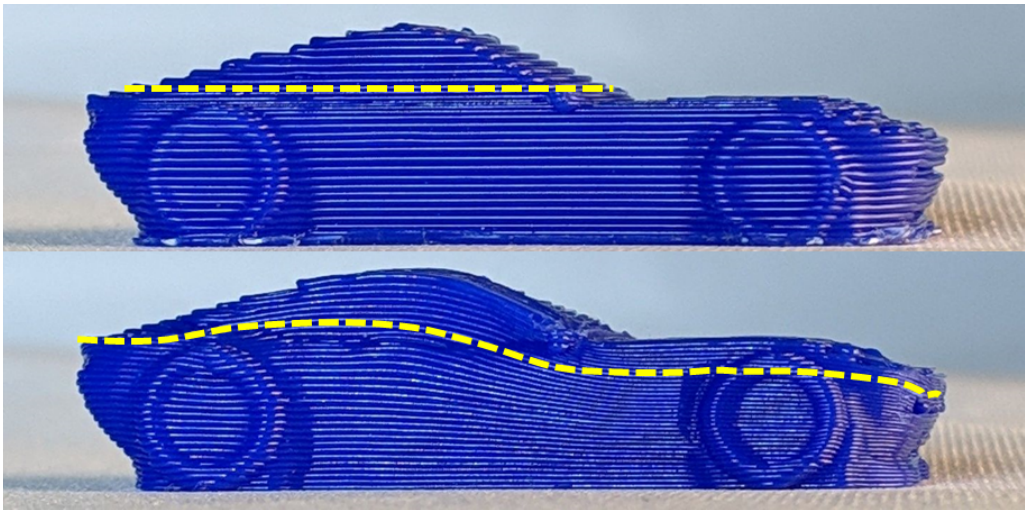


Figure 5. A 3D model printed with our technique. The algorithm automatically generates curved slices (right) to better reproduce the slanted surfaces, removing the staircase defect created by standard planar layers (top-left: standard, bottom-left: curved).

7.6. Extrusion-Based Ceramics Printing with Strictly-Continuous Deposition

Participants: Jean Hergel, Kevin Hinz, Bernhard Thomaszewski, Sylvain Lefebvre.

3D printing with extruded ceramic paste induces constraints that deviate significantly from standard thermoplastic materials. In particular existing path generation methods for thermoplastic materials rely on transfer moves to navigate between different print paths in a given layer. However, when printing with clay, these transfer moves can lead to severe artifacts and failure.

We explored how to eliminate transfer moves altogether by generating deposition paths that are continuous within and across layers. In each layer, we optimize a continuous support path with respect to length, smoothness, and distance to the model. Comparisons to existing path generation methods designed for thermoplastic materials show that our method substantially improves print quality and often makes the difference between success and failure.

This work was primarily done at the University of Montréal in collaboration with Sylvain Lefebvre. It was published in ACM Transactions on Graphics 2019 [13], and presented at SIGGRAPH Asia 2019 by Jean Hergel.

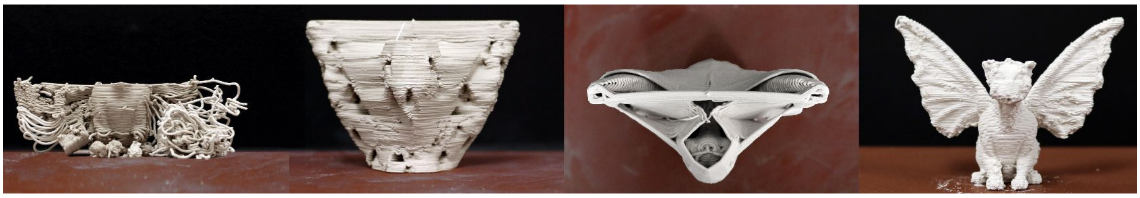


Figure 6. Our technique greatly improves the reliability of 3D printing with extruded clay.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Partnership with AddUp

- Company: AddUp.
- Duration: Started in 2019.
- Participants: Sylvain Lefebvre.
- Abstract: AddUp (https://www.addupsolutions.com/en/) is a French manufacturer of metal 3D printers for high-end industrial applications. We announced during FormNext 2019 (November) a partnership towards the creation of new software technologies.

8.1.2. Partnership with Black[Foundry]

- Company: Black[Foundry].
- Duration: January to June 2019.
- Participants: Samuel Hornus, Adrien Tétar.
- Abstract: Black[Foundry] is a company in Paris that specializes in font design. Inria signed a contract with the company to fund an internship on font rasterization on the GPU. An intern, Adrien Tétar, joined our team from January to June, and then spent 3 more weeks at the company offices in Paris. He was supervised by Samuel Hornus and Nicolas Rougier (Inria Bordeaux).

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. Project Orthosis4D (2019-2022)

- Acronym: Orthosis4D.
- Title: Passive and active 3D printed orthosis: modeling, simulation and applications.
- Duration: 2019-2022.
- Funding: Lorraine Université d'Excellence.
- Coordinator: Sylvain Lefebvre.
- Participants: SylvainLefebvre, ThibaultTricard, Pierre-AlexandreHugron, Jean-BaptisteAustruy
- Other partners: IJL, LRGP, ERPI, IRR and Nancy CHU
- Abstract: The project considers the creation of flexible plates with controlled elasticity for use in medical applications (orthoses, insoles). It exemplifies our approach of doing focused collaborations around application domains of our research, to ensure that our techniques answer actual practical challenges and maximize the chances that they are deployed in the near future. On our side the project funds a PhD student, Thibault Tricard, who started in October 2018, a project manager, Jean-Baptiste Austruy, who started in May 2019 and a design engineer, Pierre-Alexandre Hugron, who started in April 2019.

  The project resulted in several publications this year [17], [11], [14]. We are also actively working with Bernhard Thomaszewski (University of Montréal) and Mélina Skouras (Inria Grenoble) within the scope of this project.

  Pierre-Alexandre Hugron started to interact with the medical partners, following the manufacturing process of orthopedic insoles at the IRR Louis Pierquin as well as producing and discussing 3D printed samples with practitioners to better understand their expectations and requirements. In particular, extensive tests have been conducted on the fabrication of different structures and density samples to mimic the current materials of insoles. Some of these samples are currently reviewed by the CHRU. These tests have resulted in an optimization of our 3D printing processes for a better accuracy and speed.

9.2. National Initiatives

9.2.1. ANR

9.2.1.1. Project MuFFin

- Acronym: MuFFin.
- Title: Procedural Stochastic Microstructures for Functional Fabrication.
- Duration: 2018-2021.
- Funding: ANR JCJC.
- Coordinator: Jonàs Martínez.
- Participants: Jonàs Martínez, Sylvain Lefebvre, Samuel Hornus, Semyon Efremov.
- Abstract:

  MuFFin aims at contributing a unified pipeline for the efficient and scalable synthesis, visualization, and modeling of additively manufactured microstructures with tailored macroscopic physical behavior. In an interdisciplinary effort, MuFFin will blend together computer and material science perspectives to deliver an integrated approach that is both computationally and physically sound.

  We have ongoing interdisciplinary collaborations with researchers in topology optimization (Perle Geoffroy-Donders and Grégoire Allaire at École Polytechnique), material science in the context of aeronautics (Mohamed amin Ben Lassoued, Ahmed Abbad, and Guilhem Michon at ISAE-SUPAREO, Annie Ross at Polytechnique Montréal), and deformable robotics (Félix Vanneste and Olivier Goury in the DEFROST Inria team).

9.2.1.2. Project IMPRIMA

- Acronym: IMPRIMA.
- Title: Implicit modeling for additive manufacturing.
- Duration: 2019-2023.
- Funding: ANR JCJC.
- Coordinator: Cédric Zanni.
- Participants: Cédric Zanni, Sylvain Lefebvre, Melike Aydinlilar.
- Abstract:

  Project IMPRIMA seek to explore novel implicit representations in order to provide a unified approach for the modeling and slicing of both macro geometry, microstructures and gradient of material. Additionally, this research aims at a complete, tight integration of both standard boundary representations and novel implicit volume representations, allowing the best choice of representation for different parts of a design.

  We have hired Melike Aydinlilar as a PhD student, starting from November 2019. We have an ongoing collaboration on skeleton-based implicit surfaces with Évelyne Hubert and Alvaro Fuentes in the AROMATH Inria team.

9.3. International Initiatives

9.3.1. Inria International Partners

9.3.1.1. Informal International Partners

We continued our informal international collaborations, in particular with Bernhard Thomaszewski (University of Montréal) on clay support structures [13] and microstructure design [14].

We are pursuing our joint research effort on slicing and curved 3D printing [11] with Charlie C.L. Wang (The Chinese University of Hong Kong), Sara McMains (University of California Berkeley), Brian Wyvill (University of Victoria), Daniele Panozzo (NYU), and Marc Alexa (TU-Berlin).

We have an ongoing collaboration with Tim Kuipers (TU Delft/Ultimaker) on algorithms for process planning.

9.3.2. *Visits of International Scientists*

We have invited Tim Kuipers, a developer at Ultimaker in the Netherlands, and a PhD student at TU Delft, to join us on an ongoing project in which Samuel Hornus and Sylvain Lefebvre are involved together with the GAMBLE team of Inria Nancy. Tim visited us in Nancy for 3 weeks in September.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. *Scientific Events: Selection*

10.1.1.1. Chair of Conference Program Committees

- Sylvain Lefebvre was a program co-chair for the SGP 2019 graduate school.

10.1.1.2. Member of the Conference Program Committees

- Jonàs Martínez was on the full papers program committee of EUROGRAPHICS 2020.
- Sylvain Lefebvre was a conflict of interest coordinator for ACM SIGGRAPH 2019.
- Sylvain Lefebvre was on the paper advisory board of EUROGRAPHICS 2020.
- Sylvain Lefebvre was on the papers program committee of SMI 2019.

10.1.1.3. Reviewer

- Jonàs Martínez was reviewer for ACM SIGGRAPH, Pacific Graphics, and the Symposium on Solid and Physical Modeling (SPM).
- Sylvain Lefebvre was a reviewer for ACM SIGGRAPH and ACM SIGGRAPH Asia.
- Samuel Hornus was a reviewer for ACM SIGGRAPH 2019, SPM 2019 (Symposium on Physical Modeling), HPG 2019 (High Performance Graphics) and EUROGRAPHICS 2020.

10.1.2. *Journal*

10.1.2.1. Reviewer - Reviewing Activities

- Jonàs Martínez was a reviewer for the ACM Transactions on Graphics journal and the SV–Journal of Mechanical Engineering.
- Cédric Zanni was a reviewer for the Elsevier Computer and Graphics journal and the Elsevier Graphical Models journal.
- Sylvain Lefebvre was a reviewer for the ACM Transactions on Graphics journal and the Computer Aided Geometric Design journal.
- Samuel Hornus was a reviewer for the Computer Graphics Forum journal.

10.1.3. *Invited Talks*

Jonàs Martínez gave an invited talk at Journées Matériaux Numériques 2019 entitled “Generalized Voronoi Diagrams for Metamaterial Design”.

Sylvain Lefebvre gave a keynote at SCF 2019 (Pitsburg, USA), at the IS2M annual meeting (Mulhouse, France) and at the JGA 2019 (La Bresse, France).

10.1.4. *Research Administration*

Jonàs Martínez is the scientific correspondent for Europe (Inria Nancy Grand-Est). Samuel Hornus is the chair of the CDT (Commission de dévelopement technologique) of Inria Nancy Grand-Est.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Master : Jonàs Martínez, Introduction to data parallelism, 14 ETD, Université de Lorraine, France.

Master : Jonàs Martínez, Geometric modelling for additive manufacturing, 10 ETD, ENSEM Nancy, France.

Master: Cédric Zanni, Software Engineering, 13.5h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Operating System, 12h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Introduction to C/C++, 27h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Techniques for video game programming, 54h ETD, M1, École des Mines de Nancy, France.

Master: Sylvain Lefebvre, Additive manufacturing for soft robotics, 6h ETD, École Polytechnique, Saclay, France.

Master: Sylvain Lefebvre, Introduction to parallel programming, 9h ETD, ENSG Nancy, France.

Master: Sylvain Lefebvre, Introduction to additive manufacturing, 9h ETD, ENSEM Nancy, France.

License : Cédric Zanni, Computer science, 11h ETD, École des Mines de Nancy, France.

License : Cédric Zanni, Introduction to Computer Science, 13.5h ETD, École des Mines de Nancy, France.

License : Samuel Hornus, Mathematics for Computer Science, 64h ETD, Télécom Nancy, France. (responsible of class series for 2019-2020, 2020-2021.)

IUT: Thibault Tricard, Data structures, data bases, 40h ETD.

IUT: Jimmy Étienne, Introduction to programming, 64h ETD.

10.2.2. Supervision

- PhD in progress : Thibault Tricard, Procedural synthesis of structured patterns, started October 2018, advisors: Sylvain Lefebvre, Dider Rouxel (IJL).
- PhD in progress : Jimmy Étienne, Curved slicing for additive manufacturing, started September 2018, advisors: Sylvain Lefebvre, Cédric Zanni
- PhD in progress : Semyon Efremov, procedural microstructures for additive manufacturing, started October 2018, advisors: Jonàs Martínez, Sylvain Lefebvre
- PhD in progress : Melike Aydinlilar, Implicit modeling for additive manufacturing, started November 2019, advisors: Cédric Zanni, Sylvain Lefebvre.

10.2.3. Juries

Sylvain Lefebvre was reviewer (*rapporteur)* on the PhD thesis of Geoffroy Guingo (University of Strasbourg) and participated in the thesis mid-term committees of Nicolas Lutz et Pascal Guehl (University of Strasbourg).

Sylvain Lefebvre was a member of the jury for the Young Researcher Fellow EGFR, which awards every year a young French researcher with outstanding research and community contributions in the field of Computer Graphics.

10.3. Popularization

10.3.1. Articles and contents

Sylvain Lefebvre co-authored a position paper for NEM on Creative AI [18], and appeared in a short movie on the Creativ'Lab's shared fabrication space and MFX's research.

10.3.2. Interventions

In March 2019, IceSL was presented at the **Maker Faire Lille**, with a focus on color printing, printing big parts using cavities and polyfoams (all results from prior years now available in IceSL). IceSL was presented during an **Inria Tech Talk at Station-F** in Paris, along with a display of best prints [1].

In April 2019, IceSL was presented to an audience of designers for the second part of **Affinité Design** (http://www.affinitedesign.com/), with a discussion about the transition from 3D printing to "4D printing", in a joint talk with Sylvain Lefebvre, Jean-Claude André and Samuel Kenzari (http://www.nancy.archi.fr/fr/biennale-du-design-grand-est-2019_-e.html). In October 2019, Pierre Bedell and Pierre-Alexandre Hugron presented IceSL at **OctoberMAKE**, a meeting organised by the French FabLabs network (http://www.fablab.fr/octobermake/). Sylvain Lefebvre gave an IceSL tutorial at the **Soft Robotics days** in Lille (https://jrs2019.sciencesconf.org/). Sylvain Lefebvre created quick tutorial videos on Youtube (channel *icesl-fr*), to help introduce new users to IceSL.

Sylvain Lefebvre gave a presentation at **Grand-Est Numerique** 2019, geared towards start-ups, presenting results from MFX.

10.3.3. Internal action

The team actively participated to the inauguration of the Creativ'Lab space in December 2019.

11. Bibliography

Major publications by the team in recent years

[1] M. Alexa, K. Hildebrand, S. Lefebvre. *Optimal discrete slicing*, in "ACM Transactions on Graphics", February 2017, vol. 36, n^o 1, pp. 1 - 16 [*DOI :* 10.1145/2999536], https://hal.inria.fr/hal-01660773

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Articles in International Peer-Reviewed Journals

[11] J. Etienne, N. Ray, D. Panozzo, S. Hornus, C. C. Wang, J. Martínez, S. Mcmains, M. Alexa, B. Wyvill, S. Lefebvre. *CurviSlicer: Slightly curved slicing for 3-axis printers*, in "ACM Transactions on Graphics", 2019, vol. 38, forthcoming [*DOI :* 10.1145/3306346.3323022], https://hal.archives-ouvertes.fr/hal-02120033

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