Activity Report 2018

Team MFX

Matter From Graphics

RESEARCH CENTER
Nancy - Grand Est

THEME
Interaction and visualization

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Team MFX

Creation of the Team: 2018 March 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

Semyon Efremov [Inria, from Oct 2018]
Jimmy Etienne [Inria Mar-Aug 2018 then PhD CNRS from Sep 2018]
Thibault Tricard [Univ. de Lorraine, from Oct 2018]

Technical staff

Pierre Bedell [Inria, from Nov 2018]
Salim Perchy [Inria, from Mar 2018]
Noémie Vennin [Inria, from Mar-Sep 2018, Univ. de Lorraine, from Oct 2018]

Intern

Mathieu Marsot [Inria, from Jun 2018 until Sep 2018]

Administrative Assistants

Annick Jacquot [CNRS, from Jul 2018]
Virginie Priester [CNRS, from Apr 2018]
Céline Simon [Inria, from Mar 2018]

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 cost-per-unit decreases as the number of produced units increases.
- The machine setup is largely independent from 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, and 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 combine 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 allow 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 the 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. A particular emphasis is on dealing with shape complexity, revisiting design and customization of existing parts in view of novel possibilities afforded by AM, and providing a stronger integration between modeling and the capabilities of the target processes.

Specifically, we focus 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 be **later 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 [11]), can introduce new capabilities (*e.g.*, material mixing [20]) and improve part accuracy (*e.g.*, adaptive slicing [18]).

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, in the context of additive manufacturing. The second direction considers geometric and algorithmic techniques for the actual fabrication of the modeled object, further improving the capabilities of the manufacturing processes by producing improved 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 complex parts 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 starting a project around the design of orthoses which explore how our research on elasticity control scheme through microstructure geometries can be applied to this specific medical sector; see §8.1.1.

5. Highlights of the Year

5.1. Highlights of the Year

Academic Life

We had 3 publications in the top journal in our field, ACM Transactions on Graphics, including 2 from the proceedings of the ACM SIGGRAPH conference [11], [12], [13].

Cédric Zanni has been awarded an ANR JCJC 2018 project entitled IMPRIMA (Implicit modeling for additive manufacturing). IMPRIMA aims at exploring representations for the modeling, visualization and processing of both geometry and control fields for material properties within the authoring pipeline for additive manufacturing. The project will effectively start in March 2019.

Sylvain Lefebvre co-organized the first multidisciplinary workshop on academic research in additive manufacturing within the Lorraine area, which hosted 70 participants over two days. The two days workshop started on May 31, 2018 at Inria-Nancy Grand Est and was co-organized with Sandrine Hoppe (LRGP), Samuel Kenzari (IJL) and Hakim Boudaoud (ERPI). See https://www.inria.fr/centre/nancy/agenda/workshop-fa.

Creativ'Lab

Figure 1. The new MFX space within the Creativ'Lab.

The newly created experimental space for the MFX team was finished in September 2018. We are gradually moving our equipment. We worked to maximize usability and create a logical layout, organized in several spaces: one for powder devices, one for resin machines and another for filament 3D printers.

This new lab will greatly improve our capability to experiment, produce and test results.

5.1.1. Awards

Jérémie Dumas, who was advised by Sylvain Lefebvre and defended in February 2017, received the 2018 PhD prize from IG-RV (https://prixigrv2018.sciencesconf.org/).

6. New Results

6.1. Carving Large Cavities in Shapes for Fast Fused Deposition Modeling

Participants: Samuel Hornus, Sylvain Lefebvre.

FDM Fused Deposition Modeling: fabricating things by depositing fused material into layers.

In 2016, we developed a technique for modeling a tight shield that protects the part being manufactured during 3D-printing with multi-material. In particular, the shield catches oozing material before it reaches the part [19]. The technique was implemented on a voxel representation of the shape. We also demonstrated its use for the modeling of a large *self-supported* cavity inside the shape.

In this more recent work, we have extended the technique to iteratively carve large cavities in the shape in order to hollow a shape as much as possible while maintaining its ability to be fabricated without internal support. (see Figure 2) We developed a polygonal implementation of the technique that provides much higher quality results. The work was published at the 2018 Eurographics conference as a short paper [14]. An implementation is now available to the general public in our software IceSL.

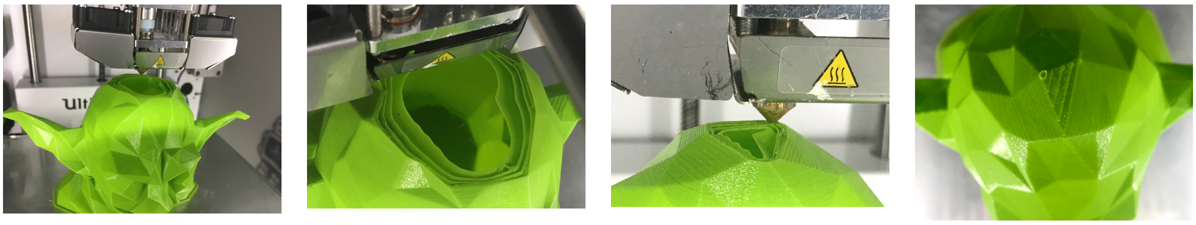


Figure 2. From Section 6.1. Timelapse of the printing of a Yoda model. (Middle-left.) Note how the print is mostly empty and the nested cavity walls. Middle-right. Approaching the top of the head. Right. Closing the top of the head.

6.2. A Metamaterial for Fused Filament Fabrication

Participants: Jonàs Martínez Bayona, Samuel Hornus, Sylvain Lefebvre.

A critical advantage of additive manufacturing is its ability to fabricate complex small-scale structures. These microstructures can be understood as a *metamaterial*: they exist at a much smaller scale than the volume they fill, and are collectively responsible for an average elastic behavior different from that of the base printing material. For instance, this can make the fabricated object lighter and/or flexible along specific directions. In addition, the average behavior can be graded spatially by progressively modifying the microstructure geometry (see Figure 3).

The definition of a microstructure is a careful trade-off between the geometric requirements of manufacturing and the properties one seeks to obtain within a shape: in our case a wide range of elastic behaviors. Most existing microstructures are designed for stereolithography (SLA) and laser sintering (SLS) processes. The requirements are however different than those of continuous deposition systems such as fused filament fabrication, for which there was a lack of microstructures enabling graded elastic behaviors.

We introduced a novel type of metamaterial that *strictly enforces* all the requirements of Fused Filament Fabrication (FFF): continuity, self-support and overhang angles. This metamaterial offers a range of orthotropic elastic responses that can be graded spatially. This allows us to fabricate parts usually reserved to the most advanced technologies on widely available inexpensive printers that also benefit from a continuously expanding range of materials.

Figure 3. A 3D printed shoe sole. Left: Control fields used on the model, density (top), orthotropy strength (middle) and angle (bottom). Right: Printed shoe, top, side and bending. The shoe is printed without any skin to reveal the foam structure.

This work was presented at the SIGGRAPH conference and published in ACM Transactions on Graphics [12], and is integrated in the publicly available IceSL software. This was a joint work with Haichuan Song, then a post-doctoral researcher in ALICE.

6.3. Topology Optimization of Parametrized Stochastic Microstructures

Participants: Jonàs Martínez Bayona, Sylvain Lefebvre.

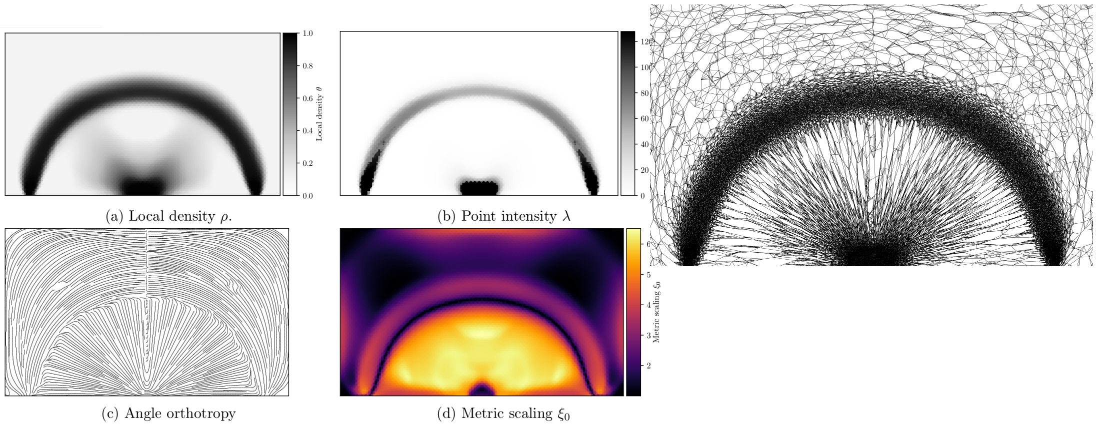
Different works have explored the topology optimization of parametrized periodic microstructures by the homogenization method. A promising venue of work lies in Additive Manufacturing technologies, that allow us to physically realize the intricate designs obtained with topology optimization. In order to fabricate the results, the parametrized microstructures must be projected at some finite scale taking into account the minimum printable size. However, for periodic microstructures it remains difficult to project and continuously grade the material properties since the boundary and transition between tiles has to be carefully handled.

We have an ongoing project in collaboration with Perle Geoffroy-Donders and Grégoire Allaire at École Polytechnique, to investigate the applicability of stochastic microstructures for topology optimization. This year we studied two different stochastic microstructures (isotropic and orthotropic) solely parametrized by an anisotropic metric and a Poisson point process. Both stochastic microstructures are amenable to efficient and scalable computation of their geometry. Unlike previous methods dealing with the projection of orthotropic microstructures the presented microstructures are able to easily follow a field of orthotropy orientation (see Figure 4).

6.4. Hash-based CSG Evaluation on GPU

Participants: Cédric Zanni, Sylvain Lefebvre.

We have developed a new evaluation scheme for Constructive Solid Geometry (CSG) modeling that is well adapted to modern GPUs. The approach falls into the category of screen space techniques and can handle a large range of geometric representations. The proposed method relies on the idea of hashing in order to reduce the memory footprint for the processing of a given ray in the scene (*e.g.*, for discovering which part of the space is within or outside the object) while allowing the evaluation of the CSG in amortized constant time. This memory reduction in turn allows the space to be subdivided in order to apply progressively the rendering algorithm, ensuring that required data fit in the graphic memory. This improvement over previous approaches allows us to handle objects of higher complexity during both modeling and slicing for additive manufacturing.



(a) Local density ρ.

(b) Point intensity λ

(c) Angle orthotropy

(d) Metric scaling ξ_0

Figure 4. Optimization of a bridge problem with an orthotropic material, and our parametric stochastic microstructure. Left: Optimized parameters of the microstructure (density, angle of orthotropy, and degree of orthotropy). Right: Projection of the stochastic microstructure at a finite scale.

The work was presented at the 2018 Symposium on Interactive 3D Graphics and Games conference and published in the ACM journal Computer Graphics and Interactive Techniques [15]. It was then integrated in the current version of our software IceSL.

6.5. Tile-based Pattern Design with Topology Control

Participant: Sylvain Lefebvre.

This project is a collaboration with Li-Yi Wei (HKU/Adobe) in the context of the PrePrint3D associated team. We consider the problem of producing tilings with boundary constraints, while enforcing global topology constraints. Tilings are composed by assembling a number of square tiles. Only tiles with compatible boundaries may be placed next to each others. In our context the tiles contain solid shapes connecting some of the borders together (corners, bars, crosses, etc.). Our algorithm is able to produce tilings that enforce border constraints as well as global topology constraints – in particular obtaining a connected network. This has applications in digital manufacturing, for instance to design decorative panels, but also in Computer Graphics, to synthesize large environments guaranteed to be navigable. These results were published in the ACM journal Computer Graphics and Interactive Techniques [10] and presented at the 2018 Symposium on Interactive 3D Graphics and Games conference.

We continue exploring tiling related problems, for instance to encode information within synthesized tilings [17].

6.6. Curved Deposition

Participants: Sylvain Lefebvre, Jimmy Etienne.

This project continues in collaboration with the ALICE team.

We are pursuing a line of research around curved deposition. The objective is to go beyond the flat-layers currently used. Indeed, some processes would allow for deposition along curved paths, however this capability is rarely used: proofs of concept exist, but no general algorithm can generate curved paths given an input geometry.

There are several key potential advantages to curved deposition: reducing the constraints in terms of geometries that can be manufactured, achieving better mechanical properties (*e.g.*, by aligning deposition with respect to a computed stress field), achieving better surface quality.

In this context, we achieved new results to reduce support material, in a joint project with Charlie C.L. Wang (TU Delft) [11]. The 3D printer is a 5-DOF robotic arm equipped with a standard FDM extruder. The algorithm we developed is based on a heuristic growth process within a discretized version of the model (voxels). The growth process attempts to place additional material where it is already supported from below, while avoiding cases where some unfinished parts of the model would become inaccessible due to collisions.

This led us to the first general algorithm for multi-axis 3D printing. It produces tool-paths that allow the robotic arm to fabricate most parts without any support, while avoiding collisions. Many challenges remain, both related to geometry and robotics, and we are pursuing this collaboration, jointly with Nicolas Ray (ALICE-Inria).

6.7. Colored 3D Printing

Participants: Sylvain Lefebvre, Jonàs Martínez Bayona, Noémie Vennin, Pierre Bedell.

In 2018 we kept developing our project regarding colored FDM printing. We have a paper accepted with minor revisions in ACM Transactions on Graphics. This was a joint work with Haichuan Song, then a post-doctoral researcher in ALICE. We worked on revising and refining our initial results throughout the year.

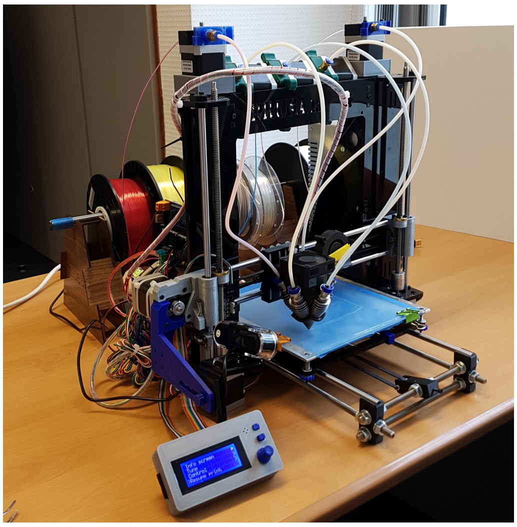


Figure 5. 3D printer Diamonds 5 filaments.

We proposed a novel algorithm for the problem of determining micro-layer mixtures to reproduce a subspace of material mixing ratios. We express the problem as fitting a simplex of minimal volume enclosing a set of points. The vertices of the simplex correspond to micro-layer mixtures, while the point set captures the desired mixtures within the model. This algorithm replaces the previous non-linear, gradient based optimizer. It achieves better results at a fraction of the previous computation time.

We also developed, through the internship of Pierre Bedell, a 3D printer able to mix up to five filaments. We ran extensive testing and implemented additional improvements regarding flow control during deposition. Pierre Bedell joined the team as a research engineer and will keep participating in this project.

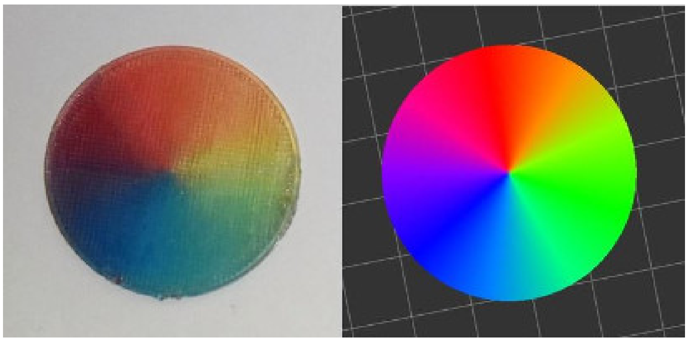


Figure 6. Disc showing all the gradation of color with 3 filaments (red, yellow, blue). Left: 3D printed disc. Right: Numerical view on the software IceSL.

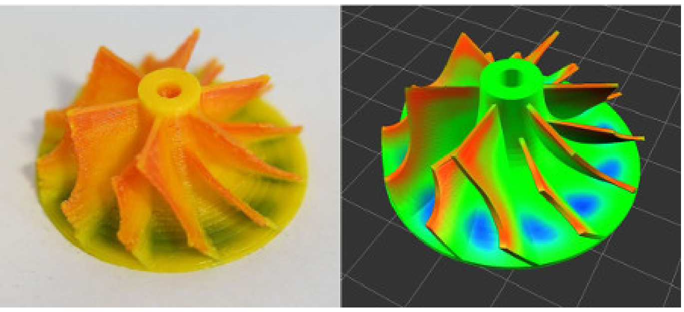


Figure 7. Turbine with a colored simulation of friction. Left: 3D printed turbine. Right: Numerical view on the software IceSL.

Noémie Vennin joined the team on a funding from *Université de Lorraine* to explore material aspects of the project, in a close collaboration with Sandrine Hoppe (LRGP). This part of the project receives support from the CPER Cyber-entreprise, thanks to which we acquired equipment to develop our own filament formulations, mixing pigments and additives to control color and transparency. Pierre Bedell and Noémie Vennin are developing a calibration process to determine the achievable color space given specific filaments, but also to tackle the inverse problem of designing filaments spanning a desired color space.

6.8. IceSL

Participants: Sylvain Lefebvre, Salim Perchy, Cédric Zanni, Samuel Hornus, Jonàs Martínez Bayona, Jimmy Etienne, Noémie Vennin, Pierre Bedell.

IceSL is the software developed within the team 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 at https://icesl.loria.fr, both as a desktop and an online version.

In 2018, 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.

In February 2018, we organized the first event to introduce basic and advanced features which differentiate IceSL from other 3D printing tools. The event, targeted towards enthusiasts, allowed its participants to follow tutorials, interact with its developers and suggest additions and new directions for the software.

IceSL was also presented in May 2018 at the Strasbourg's Mini MakerFaire to a general audience that included high school students. The audience was introduced to IceSL's new features first hand and their applications to 3D printing. In addition to this, IceSL was shown to designers in November 2018 at Affinité Design (http://www.affinitedesign.com/) with part of the developing team demonstrating and answering questions on the use of IceSL as a modeling tool.

In October 2018, both the desktop and the online versions of IceSL were featured in a list of the 24 best 3D printing software tools. [1]

Regarding new features and additions to the software in 2018, IceSL has added several innovative methods for modeling and slicing. With respect to modeling, these include the ability to interactively paint values in a script (field tweaks), the option to export the shape generated with CSG to a mesh via dual contouring, texture synthesis on 3D objects, better font geometry creation as well as numerous improvements on its user interface and compatibility with hardware.

On the slicing front, IceSL has introduced new material infilling methods such as *polyfoam* [12], progressive and cubic structures (Figure 8) as well as putting a system in place allowing the user to specify an infill pattern through program image assets or shaders.

IceSL also added a new method to compute supports called "wings," a new framework for mixing colors into a 3D print [20] (presented in several exhibitions), curved printing covers, a faster slicing algorithm (in case of tessellated geometry), and a new geometry renderer [15].

The social community of IceSL is also growing accordingly. Its twitter account has around 200 followers and there are 150 users frequently interacting in its google forum. Downloads have increased around 30% after the first event in February 2018 to make a cumulative of 30k downloads since its initial release. [2] Youtube videos done by third persons on the usage of IceSL are also common (around a dozen in three different languages). And finally, in October 2018 IceSL launched its new website with a more professional look and additional resources (documentation, tutorials, videos, online version and new features).

6.9. Chill

Participants: Jimmy Etienne, Sylvain Lefebvre.

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[1] https://all3dp.com/fr/1/meilleur-logiciel-imprimante-3d-gratuit-en-ligne/

[2] See https://gforge.inria.fr/top/toplist.php?type=downloads. Due to the removal of a file, the download counter on gforge.inria.fr is off by 6000 downloads.

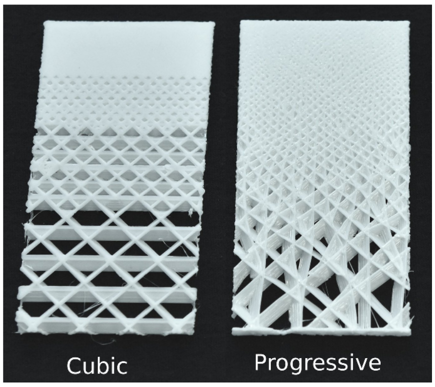

Figure 8. New infill patterns introduced in IceSL, the left one (cubic) has now been adopted by most other slicing software.

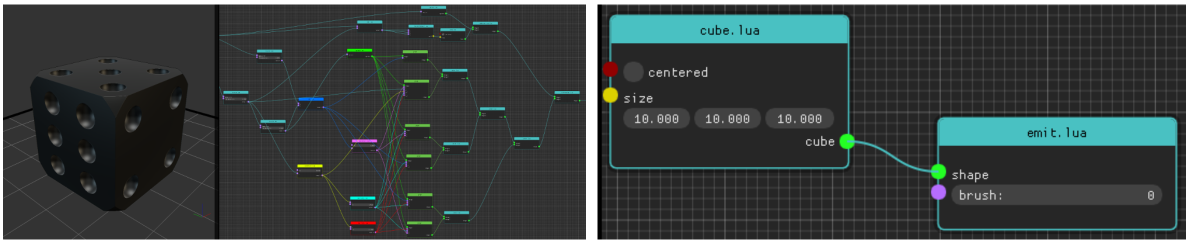

Figure 9. The Chill node-based GUI.

Chill is an open source GUI for IceSL, illustrated in Figure 9. It features a node-based interface that hides the scripting language used to model shapes in IceSL. This enables a larger group of people to use IceSL in their projects, without having to type any code. The user of Chill creates 3D shapes by connecting various nodes arranged in a directed graph. The shape visualization is updated instantly as the graph is modified.

The source code is publicly available at https://github.com/shapeforge/Chill. We are planning to communicate broadly about the software in the first months of 2019.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

In 2018 we had several discussions and collaborations with industrial partners, one leading to an active R&D collaboration contract. All are confidential.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. Project LUE

- Funding type: Lorraine Université d'Excellence.
- Title: Passive and active 3D printed orthosis: modeling, simulation and applications.
- Project Coordinator: Sylvain Lefebvre

This project is funded by *Lorraine Université d'Excellence* for three years. It is a collaboration between IJL (Jean Lamour Institute), LORIA (Lorraine Research Laboratory in Computer Science and its Applications), LRGP (Reaction and Process Engineering Laboratory), ERPI (Research Laboratory on Innovation Process), IRR Nancy (Regional Institute for Physical and Rehabilitation Medicine) and Nancy CHU (University Hospital). 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.

The project funds a PhD student, Thibault Tricard, who started in October 2018. Thibault is co-advised by Sylvain Lefebvre and Didier Rouxel (IJL).

8.1.2. Project PIC

- Funding type: Pacte Lorraine.
- Title: Innovative Polymers and Composites
- Project Coordinator: Sylvain Lefebvre

The project PIC (*Innovative Polymers and Composites*) is a regional project between Inria, IJL (Jean Lamour Institute – materials science), ECN (surgery school) and the company *Les Ateliers Cini*. This collaboration aimed for the creation of new high performance composite materials usable in 3D printing. It began in 2016 (within ALICE) and ended in 2018 (within MFX). The project funded an engineer, Noémie Vennin.

MFX contributed on algorithm aspects of the 3D printer control. PEEK is a material that needs a strict control of temperature: it is extruded at 400 degrees, and cooling plays an important role in the final mechanical properties. During the project, we first developed the software possibilities, adding novel features to enable a finer control over deposition and temperature management. These improvements were implemented in our IceSL software and included thermal shields (see Figure 10), novel support structures, novel infill patterns and the ability to control all print parameters within the object (*e.g.*, varying temperature in different parts). This lead to a significant increase in part quality and accuracy. We also worked on improving the 3D printer jointly with other partners, upgrading the thermal capabilities with a better heating plate (+40°C) and side mounted heating patches, with a safety and control sensor.

Figure 10. 3D printed vase in PEEK material. Left: Vase breaking during fabrication due to thermal stresses. Right: Adding a thermal shield (not shown) results in a correct 3D print.

We are now able to produce parts in PEEK material, using IceSL for generating printer instructions. For instance, we manufactured parts used by the surgery school for training sessions.

Nevertheless, despite improvements in print quality, it remains the case that parts should be designed or modified to achieve best results with PEEK filament deposition. The high temperature gradients and thermal behavior of PEEK remain very challenging and constrain the geometries that can be reliably produced.

8.1.3. Project Colored FDM

- Funding type: CPER and LORIA
- Title: Color fused filament deposition
- Project Coordinator: Sylvain Lefebvre

This project is funded both by the CPER Cyber-entreprise (axis *algorithms for novel materials*) and the LORIA laboratory. As part of the CPER, we work closely with the *Reaction and Process Engineering Laboratory* (LRGP) in Nancy on this topic.

8.1.4. Regional PhD Funding

- Funding type: Région Grand-Est.

We secured two half-PhD fundings from Région Grand-Est in 2018. The first is co-funding Semyon Efremov (PhD student) in the context of the ANR MuFFin. Semyon is co-advised by Jonàs Martínez and Sylvain Lefebvre, he joined the team in October 2018.

The second is co-funding Jimmy Etienne (PhD student), co-advised by Cédric Zanni and Sylvain Lefebvre. The other half-funding is provided by local support from the LORIA laboratory. Jimmy Etienne's topic focuses on curved printing for additive manufacturing, he started in September 2018.

8.2. National Initiatives

8.2.1. ANR

8.2.1.1. Project MuFFin (2018-2021)

- Funding type: ANR JCJC (ANR-17-CE10-0002).
- Title: Procedural and stochastic microstructures for functional fabrication
- Project Coordinator: Jonàs Martínez

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.

This year we hired Semyon Efremov as a PhD student, starting from October 2018. We have interdisciplinary collaborations with researchers in topology optimization (Perle Geoffroy-Donders and Grégoire Allaire at École Polytechnique), and material science in the context of aeronautics (Mohamed amin Ben Lassoued and Guilhem Michon at ISAE-SUPAREO, Annie Ross at Polytechnique Montréal).

8.3. International Initiatives

8.3.1. Inria International Partners

8.3.1.1. Informal International Partners

In 2018 we had collaborations with TU Delft [11], continued collaborations with Connelly Barnes (Adobe) [17] and Li-Yi Wei (Adobe) [17], [10]. We have ongoing projects with Bernhard Thomaszewski (University of Montreal), Daniele Panozzo (NYU), Marc Alexa (TU-Berlin), Charlie C.L. Wang (TU-Delft), Sara McMains (University of California) and Brian Wyvill (University of Victoria).

8.4. Visits of International Scientists

Brian Wyvill, professor at the University of Victoria, is a pioneer in the field of computer graphics. He visited us on May 10-11, 2018 and gave a seminar to the department.

Jean-Baptiste Labrune, designer and researcher in 4D printing visited on November 29, 2018. We organized an open seminar within LORIA.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific Events Organisation

Sylvain Lefebvre co-organized the first multidisciplinary workshop on academic research in additive manufacturing within the Lorraine area, which hosted 70 participants over two days. The two days workshop started on May 31, 2018 at Inria-Nancy Grand Est and was co-organized with Sandrine Hoppe (LRGP), Samuel Kenzari (IJL) and Hakim Boudaoud (ERPI). See https://www.inria.fr/centre/nancy/agenda/workshop-fa.

9.1.2. Scientific Events Selection

9.1.2.1. Member of Conference Program Committees

- Samuel Hornus was on the program committee for the “short papers track” at Eurographics.
- Jonàs Martínez was on the program committee of Pacific Graphics and the “short papers track” at Eurographics.
- Sylvain Lefebvre is on the advisory board of the technical paper committee of EUROGRAPHICS 2019.

9.1.2.2. Reviewer

Jonàs Martínez and Sylvain Lefebvre were reviewers for SIGGRAPH and SIGGRAPH Asia.

9.1.3. Journal

9.1.3.1. Reviewer - Reviewing Activities

- Samuel Hornus did some reviewing for ACM Transactions on Graphics and Computer Graphics Forum.
- Jonàs Martínez was reviewer of Computer Aided Geometric Design (Elsevier) and Transactions on Visualization and Computer Graphics (IEEE).

9.1.4. Invited Talks

Jonàs Martínez gave an invited talk in Journées Scientifiques Inria 2018.

Sylvain Lefebvre gave a one hour class at the 2018 SPG Graduate School (https://sgp2018.sciencesconf.org/resource/page/id/7). He was keynote speaker at the WCCM workshop *Expanding the Frontiers of Engineering Design using Computation* (http://www.wccm2018.org/MS_1407). Sylvain also gave an invited talk at the JIGS (*Journées Informatique et Géométrie 2018*, June 21-22).

9.1.5. Scientific Expertise

Sylvain Lefebvre participated in a strategy meeting at ANRT on the topic of 4D printing, on November 12, 2018.

9.1.6. Research Administration

Samuel Hornus leads the local "Commission du Dévelopement Technologique." Sylvain Lefebvre joined the Inria center *bureau du comité des projets* (BCP) in November.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

École d'ingénieur : Samuel Hornus, Mathématiques pour l'informatique, 32 HeqTD, niveau L1, Télécom Nancy, France.

Master 1: Jonàs Martínez, Infographie, 24 HeqTD, Université de Lorraine, France.

Master 1: Jonàs Martínez, Introduction au parallélisme de données, 12 HeqTD, Université de Lorraine, France.

PhD School: Jonàs Martínez, International School on Graphics and Geometry Processing for Digital Manufacturing, 3h, Italy.

École d'ingénieur : Cédric Zanni, Informatique 1, 20h ETD, niveau L3, École des Mines de Nancy, France.

École d'ingénieur : Cédric Zanni, Informatique 2, 27.5h ETD, niveau L3, École des Mines de Nancy, France.

École d'ingénieur : Cédric Zanni, Introduction au Parcours Information et Systèmes 13.5h ETD, niveau L3, École des Mines de Nancy, France.

Master: Cédric Zanni, Software Engineering, 20h 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 au C/C++, 27h ETD, M1, École des Mines de Nancy, France.

Master: Cédric Zanni, Techniques de l'animation et du jeu vidéo, 27h ETD, M1, École des Mines de Nancy, France.

Master: Sylvain Lefebvre, Programmation pour le jeu vidéo, 12h ETD, École des Mines de Nancy, France.

Master: Sylvain Lefebvre, Introduction au parallélisme et au graphisme, 9h ETD, ENSG Nancy, France.

Master: Sylvain Lefebvre, Introduction à la fabrication additive, 9h ETD, ENSEM Nancy, France.

9.2.2. Supervision

PhD in progress : Thibault Tricard, *Multi-material microstructures*, started in October 2018, co-advised by Sylvain Lefebvre and Didier Rouxel (Institut Jean Lamour).

PhD in progress : Jimmy Etienne, *Curved additive manufacturing*, started in September 2018, co-advised by Sylvain Lefebvre and Cédric Zanni.

PhD in progress : Semyon Efremov, *Stochastic procedural microstructures: 3D modeling and analysis*, started in October 2018, co-advised by Jonàs Martínez and Sylvain Lefebvre.

9.2.3. Juries

Sylvain Lefebvre was reviewer for the HdR thesis of Basile Sauvage (ICube, Strasbourg, France). He also served on the mid-PhD juries of Pascal Guehl (Icube) and Tim Kuipers (TU-Delft).

9.3. Popularization

9.3.1. Ada Lovelace Day

In the context of the Ada Lovelace Day, 9th October 2018, Noémie Vennin received about twenty young girls in our 3D printer room. The Ada Lovelace Day is an international celebration of the achievements of women in science, technology, engineering and maths (STEM). It aims to increase the profile of women in these fields and, in doing so, create new role models who will encourage more girls into STEM careers and support women already working in.

Figure 11. Ada Lovelace Day at MFX Team.

9.3.2. IceSL Event for non-academic users

The IceSL event was held on February 22, 2018 in Paris. The objective was to bring together our community as well as new users. We invited external users, industrial partners and FabLabs at large (through national mailing lists).

The program (https://www.weezevent.com/icesl) involved training with the software (by all the IceSL team members, 6 sessions in total), then we had our most experienced users present advanced use of IceSL: advanced modeling with implicit volumes by Loic Fejoz, modeling of orthopedic braces by Pierre Alexandre Hugron, the making-of of a complex table with our partner Creative Industry. We finally had a social event with an exhibition of our best parts.

The gathering was a success, with 50 attendees – the maximum we could host – from a variety of backgrounds (makers and industry). Following the event we saw a clear growth in the interest around the software, with a tripled visit rate to our website and a steep increase in downloads (25% additional downloads since then). The French IceSL community is especially active, with 15% of our total visits, just after the United States (23%).

We are scheduled to repeat this event (in a more compact format) in March 2019 at Station F, in Paris.

10. Bibliography

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