RESEARCH CENTRE

Inria Centre at Université de Lorraine

IN PARTNERSHIP WITH:

Université de Lorraine

2023 ACTIVITY REPORT

Project-Team MFX

Matter from Graphics

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

DOMAIN

Perception, Cognition and Interaction

THEME

Interaction and visualization

Contents

Project-Team MFX

Creation of the Project-Team: 2019 November 01

Keywords

Computer sciences and digital sciences

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 members, visitors, external collaborators

Research Scientists

- Sylvain Lefebvre [Team leader, Inria, Senior Researcher, HDR]
- Xavier Chermain [Inria, ISFP]
- Jonàs Martínez Bayona [Inria, Researcher]
- Camille Schreck [Inria, ISFP]

Faculty Member

- Cedric Zanni [UL, Associate Professor]

Post-Doctoral Fellow

- David Jourdan [Inria, Post-Doctoral Fellow]

PhD Students

- Melike Aydinlilar [UL, until Sep 2023]
- Marco Freire [UL]
- Luis Mollericon Titirico [Inria]

Technical Staff

- Pierre-Alexandre Hugron [Inria, Engineer]
- Nathaniel Seyler [Inria, Engineer, until Sep 2023]

Interns and Apprentices

- Morgan Mellinger [UL, from Mar 2023 until Aug 2023]
- Axel Stengel [ENS RENNES, Intern, from May 2023 until Jul 2023]

Administrative Assistant

- Cécilia Olivier [Inria, from Jul 2023]

Visiting Scientist

- Emilio Ottonello [Istituto Italiano di Tecnologia, from Oct 2023]

2 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.

With CAM technologies, the advent of Additive Manufacturing (AM) (i.e., 3D printing) and 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 in most situations, the cost is not significantly impacted by the geometric complexity.
- The cost-per-unit for fabricating an object is constant and significantly lower than producing a small series of objects with traditional means. However, 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. This makes them accessible to the general public and well-suited for rapid design iterations and prototyping.

Consequently, designing and producing parts with short development cycles becomes possible: 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 significant 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 pushes 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. Such quantity of details modeling becomes intractable, and specifying the geometry with standard tools becomes daunting, even for experts. Besides, 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.

We aim to develop novel approaches enabling experts and practitioners to exploit AM's advantages fully. We aim to achieve this by developing novel algorithms automatically synthesizing or completing designs with functional details. We consider the entire chain, from modeling to geometry processing, to optimize 3D printer instructions.

3 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 given the novel possibilities afforded by AM, and providing a stronger integration between modeling and the capabilities of the target processes.

We tackle 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 challenges above by considering modeling and fabrication as a single, unified process. Thus, the modeling techniques we seek to develop will consider the geometric constraints imposed by the manufacturing processes (minimal thickness, overhang angles, trapped material) and the desired object functionality (rigidity, porosity). To allow for the modeling of complex shapes and adapt the same initial design to different technologies, we propose developing techniques that can automatically synthesize functional details within parts. At the same time, we will explore ways to increase the manufacturing processes' versatility through algorithms capable of exploiting additional degrees of freedom, introducing new capabilities, and improving part accuracy.

Our research program is organized along with three main research directions. The first focuses on the automatic synthesis of shapes with intricate multi-scale geometries conforming 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 manufacturing processes' capabilities with novel deposition strategies. The third direction focuses on computational design algorithms to help model parts with a gradient of properties and help customize 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 variously industrial sectors to benefit more strongly from the potential of AM. To enable this, we seek collaborations with crucial 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.

5 Social and environmental responsibility

5.1 Footprint of research activities

Our environmental footprint is limited. We use various products for 3D printing but in small quantities, and have put in place all required measures for recycling and disposal.

5.2 Impact of research results

We make our software IceSL freely available to the public and have continued this year to document its features, organize tutorials and demonstrations (e.g. at 3DPrint Paris), as well as animate our social media accounts. Through this, we hope to encourage adoption of our research and maximize its impact, in particular by encouraging its use within the maker communities.

A longer-term strategy of the team is to help develop potential uses of our technique in different fields. This is for instance a key motivation for our participation in the DORNELL challenge, which seeks to improve devices helping the mobility impaired.

The exploratory action AEX CONTINUA emphasizes applications using 3D printing technology to construct large-scale structures to safeguard marine habitats vulnerable to rising temperatures due to global warming. We have an ongoing collaboration with researchers of CNRS (Serge Planes) and ENS Ulm (Emmanuel Dormy) that seeks to tackle this particular problem in the case of coral reefs.

6 Highlights of the year

In 2024 we acheived two important new results, both inscribed in our long term research objectives of freely orientable structures and trajectories. This led to two new publications at respectively SIGGRAPH and SIGGRAPH Asia, the first regarding appearance control [8] and the second regarding shape deformation control [10], which received a Honorable Mention at SIGGRAPH Asia 2023.

6.1 Awards

Thibault Tricard received a PhD thesis prize from the GdR IG-RV. He was co-advised by Sylvain Lefebvre and Didier Rouxel (IJL/CNRS).

Our paper on morphing 3D printed plates [10], first authored by David Jourdan, received a Honorable Mention at SIGGRAPH Asia 2023, which was awarded to the top 5% of the papers presented there.

7 New software, platforms, open data

7.1 New software

7.1.1 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 as 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: Our software IceSL, a modeler and slicer, offers the user many state-of-the-art 3D printing techniques born out of the research done by the MFX. The general goal is to make MFX's results available to the general public through IceSL's framework. Until now, the application has had 180K downloads since its release date where 4K have been attributed solely to its latest stable release. The software is released under Windows and Linux, with also an online version requiring no installation. This version has almost 100K uses since its inception and generates 75 uses per day in average.

IceSL also has a vibrant community with more than 1K followers on its X account and a technical support hub on google groups. IceSL has also been shown lately at important venues such as 3D Print Paris (2023) and VivaTech (2023) as well as more focused seminars like Fablabs hosted by Inria's SED department and at external private courses.

New features being explored this year are a resin printing component, an efficient module for optimizing orientation in filament printing, Python bindings to IceSL's slicing pipeline and an automatic image-based checker of G-code output for continuous delivery.

URL: https://icesl.loria.fr

Authors: Sylvain Lefebvre, Frédéric Claux, Jonas Martinez Bayona, Jean Hergel, Jérémie Dumas, Samuel Hornus, Yamil Salim Perchy Bocanegra, Cedric Zanni, Pierre Bedell, Jimmy Etienne, Haichuan Song, Thibault Tricard, Pierre-Alexandre Hugron, Nathaniel Seyler

Contact: Sylvain Lefebvre

7.1.2 Silice

Name: Silice

Keywords: FPGA, Programming

Functional Description: Silice makes it possible to write algorithms for FPGAs in the same way we write them for processors: defining sequences of operations, subroutines that can be called, and using control flow statements such as while and break. At the same time, Silice lets you fully exploit the parallelism and niceties of FPGA architectures, describing operations and algorithms that run in parallel and are always active, as well as pipelines. Silice remains close to the hardware: nothing gets obfuscated away. When writing an algorithm you are in control of what happens at which clock cycle, with predictable rules for flow control. Clock domains are exposed. In fact, Silice compiles to and inter-operates with Verilog: you can directly instantiate and bind with existing modules.

Release Contributions: 2021 version.

News of the Year: This year Silice continued to evolve, with the ability to create complex pipeline structures (including nested pipelines), as well as an instantiation-time pre-processor supporting recursive declarations. This allows to write generic hardware units that can be reused in various designs. Silice was also used to explore automated hardware synthesis from RISC-V assembly, a project called Iron that was presented as a poster at the RISCV summit in Barcelona (5-9 June 2023). Silice's library of hardware units continues to develop, with novel and improved memory controllers for flash and PSRAM.

URL: https://github.com/sylefeb/Silice

Author: Sylvain Lefebvre

Contact: Sylvain Lefebvre

7.2 New platforms

Participants: 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.

In the context of the AEX CONTINUA, we have acquired and set up a clay 3D printer (Lutum 4) to be able to do experimentation with viscous material. We have created and tested a profile to use this machine within our software IceSL. This equipment is taking significant space, and thus required an important reorganization of this space.

Maintenance. We performed maintenance operations on our largest 3D printer (Strateo dual) and installed a new, improved build plate. We are sharing this machine with Larsen team to make large robotic parts. We did a complete change of filters and activated carbon filters of our laser cutter. This machine was used for the publication "PCBend" and also in the context of ongoing research by Camille Schreck (DORNELL).

Resin printing platform. This platform is shared and co-operated with the LARSEN team. In the context of the ERC KARST, we have acquired and set up 3 new high resolution SLA resin printers:

Figure 1: The two main 3D printing rooms of the Creativ'Lab platform.

- 2 Phrozen Mega 8K (printing volume 33 x 18.5 x 40 cm)
- 1 Phrozen Mighty 8K (printing volume 21 x 12 x 23 cm)

We have also acquired corresponding cleaning stations and UV curing boxes for the post processing for the printed parts. The objective is to establish a process for 3D printing opticaly transparent parts allowing flow measurements, in the context of the ERC project KARST.

Robotic 3D printing. For the research on non planar-planar 3D printing conducted by Emilio Ottonello (visiting PhD student from the Istituto Italiano di Tecnologia), we did a full revision of our industrial robot (software in particular) and designed a special fan cooling duct to avoid collisions during non-planar printing.

Printing room and workshop. Some modification on the Z axis were performed on two of our CR10S Pro for increasing reliability of the bed probing for our publication “anisotropic appearance” and “shrink and morph”, for which fabricated parts required a really precise first layer calibration.

A chocolate extruder based on an open-source clay extruder was developped. One of our CR10S Pro printer was modified to be able to change and install easily different tool heads.

Finally, we bought and installed a new FDM 3D printer (Creality K1 Max), this printer can print five times faster than our other 3D printers, at greater accuracy and quality. It will help us for our research regarding trajectory generation for fast 3D printing.

7.3 Open data

8 New results

8.1 Inverse-designed Growth-based Cellular Metamaterials

Participants: Sikko Van 't Sant, Jonàs Martínez, Prakash Thakolkaran, Sid Kumar.

Advancements in machine learning have fueled interest in crafting mechanical metamaterials, where properties stem from the low-scale microstructure geometry rather than the constituent material alone. In collaboration with TU Delft (Netherlands) researchers, we introduced a data-driven exploration of growth-based cellular metamaterials using star-shaped distances. These 2D metamaterials feature periodically repeating unit cells with intricate material and void patterns. Machine learning models leverage extensive datasets to design growth-based metamaterials, tailoring anisotropic stiffness inversely. Initially, a forward model is established to predict mechanical properties accurately, bypassing the growth and homogenization process based on a finite set of design parameters. Subsequently, an inverse model inverts structure-property maps, enabling precise prediction of designs for a specified anisotropic stiffness query. Our framework's robust generalization capabilities were demonstrated by successfully inverse designing for stiffness properties beyond the initially defined design space.

This work was published in the journal Mechanics of Materials [11] and the code is available on github.

8.2 Orientable Dense Cyclic Infill for Anisotropic Appearance Fabrication

Participants: Xavier Chermain, Cédric Zanni, Jonàs Martínez, Pierre-Alexandre Hugron, Sylvain Lefebvre.

We present a method to 3D print surfaces exhibiting a prescribed varying field of anisotropic appearance using only standard fused filament fabrication printers. This enables the fabrication of patterns triggering reflections similar to that of brushed metal with direct control over the directionality of the reflections. Our key insight, on which we ground the method, is that the direction of the deposition paths leads to a certain degree of surface roughness, which yields a visual anisotropic appearance. Therefore, generating dense cyclic infills aligned with a line field allows us to grade the anisotropic appearance of the printed surface. To achieve this, we introduce a highly parallelizable algorithm for optimizing oriented, cyclic paths. Our algorithm outperforms existing approaches regarding efficiency, robustness, and result quality. We demonstrate the effectiveness of our technique in conveying an anisotropic appearance on several challenging test cases, ranging from patterns to photographs reinterpreted as anisotropic appearances.

This work was published in the ACM Transactions on Graphics journal [8], presented at the conference Special Interest Group on Computer GRAPHics and Interactive Techniques (SIGGRAPH) 2023, has been awarded the Replicability Stamp, and the code is available on github.

8.3 PCBend: Light Up Your 3D Shapes With Foldable Circuit Boards

Participants: Marco Freire, Manas Bhargava, Camille Schreck, Pierre-Alexandre Hugron, Bernd Bickel, Sylvain Lefebvre.

In collaboration with the Institute of Science and Technology Austria, we propose a computational design approach for covering a surface with individually addressable RGB LEDs, effectively forming a low-resolution surface screen. To achieve a low-cost and scalable approach, we propose creating designs from flat PCB panels bent in-place along the surface of a 3D printed core. Working with standard rigid PCBs enables the use of established PCB manufacturing services, allowing the fabrication of designs with several hundred LEDs.

Our approach optimizes the PCB geometry for folding, and then jointly optimizes the LED packing, circuit and routing, solving a challenging layout problem under strict manufacturing requirements. Unlike paper, PCBs cannot bend beyond a certain point without breaking. Therefore, we introduce

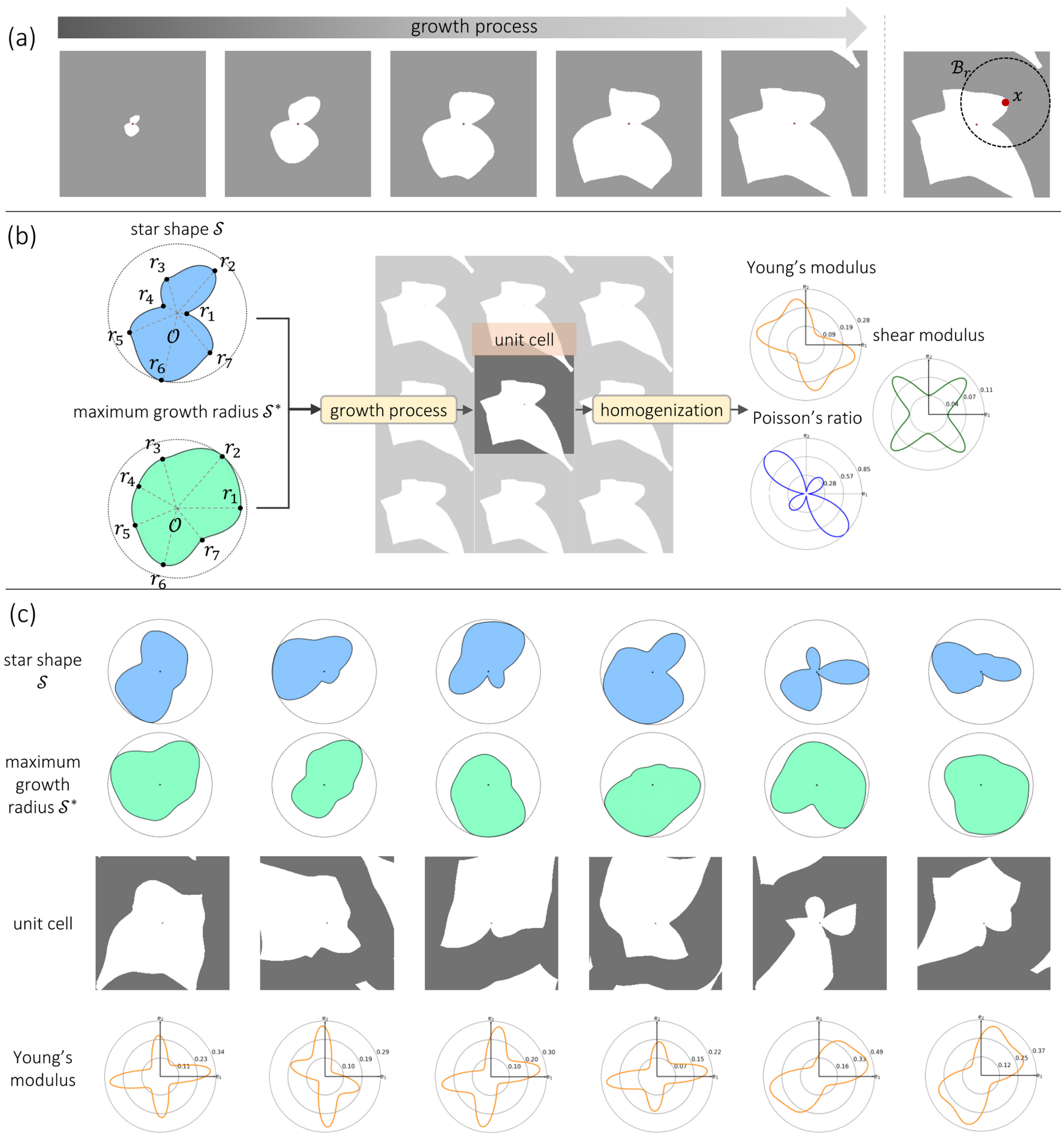


Figure 2: (a): Illustration of the discrete growth process and its stopping criterion. (b): The growth algorithm utilizes a nucleating star shape and maximum growth radius for microstructure creation. The final unit cell is formed by solidifying space outside the star shape and leaving the rest void. This black-and-white image undergoes FFT-based homogenization (with periodic boundary conditions) to extract the effective stiffness tensor. Directional properties like Young's modulus, shear modulus, and Poisson's ratio are derived from the stiffness tensor, with polar plots representing effective properties in each direction. (c): Diverse microstructures and their directional Young's moduli are showcased.

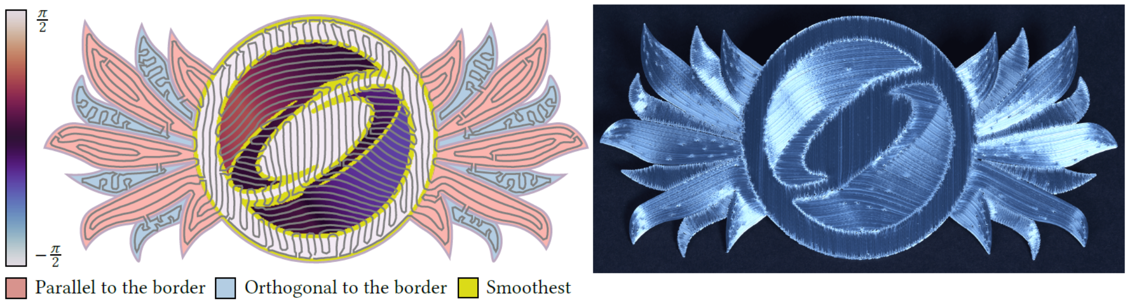


Figure 3: We develop an efficient algorithm that produces an orientable dense cyclic infill by aligning a field of periodic functions, contouring it to obtain cycles, and connecting all cycles into one. We leverage this algorithm to print anisotropic appearances using fused filament fabrication. *Left*: the shape with purple boundaries is infilled with a cycle. The cycle's directions have four modes: parallel to the boundary (red area), orthogonal to the boundary (blue area), smoothest lines (yellow area), and constrained lines (color gradient area). Our algorithm is very flexible, allowing directions to be constrained everywhere (areas with a color gradient in the logo) or only within the vicinity of the boundary (blue, red, and yellow areas). Alignment with boundaries can also be constrained, as in this example. The grey cycle is the output of our algorithm (curve interspace objective: 2.5 mm). *Right*: Printed cycle with interspace set to 0.4 mm. The trajectory's directions determine the appearance, as extruded filaments exhibit anisotropic roughness.

parametric cut patterns acting as hinges, designed to allow bending while remaining compact. To tackle the joint optimization of placement, circuit and routing, we propose a specialized algorithm that splits the global problem into one sub-problem per triangle, which is then individually solved.

Our technique generates PCB blueprints in a completely automated way. After being fabricated by a PCB manufacturing service, the boards are bent and glued by the user onto the 3D printed support. We demonstrate our technique on a range of physical models and virtual examples, creating intricate surface light patterns from hundreds of LEDs.

This work was published in the ACM Transactions on Graphics journal [9] and presented at the Special Interest Group on Computer GRAPHics and Interactive Techniques (SIGGRAPH) 2023 conference. This work was also showcased at the "Bring your own Bunny" fabrication meetup at the SIGGRAPH 2023 conference. Code and data are available on github.

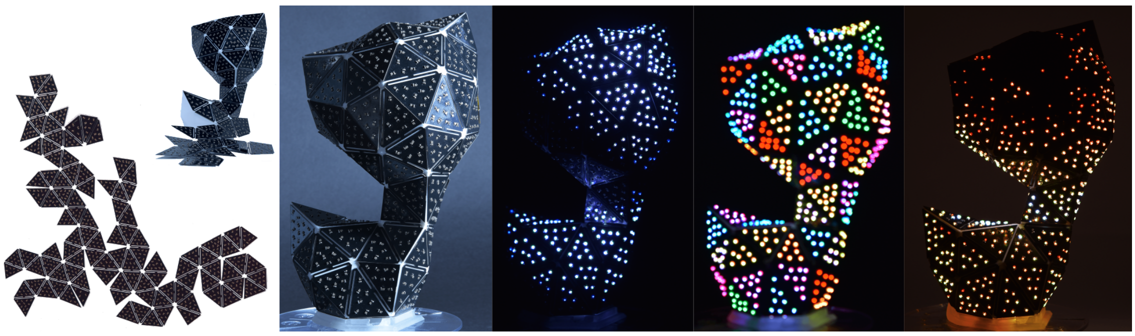


Figure 4: Starting from a 3D mesh our method automatically generates design files to produce an on-surface display composed of individually addressable RGB LEDs. The circuit board is manufactured through standard PCB production services, including component soldering. The user then folds the fabricated board back onto a 3D printed support. The final model becomes a curved display, onto which intricate light patterns can be programmed in a shader-like manner.

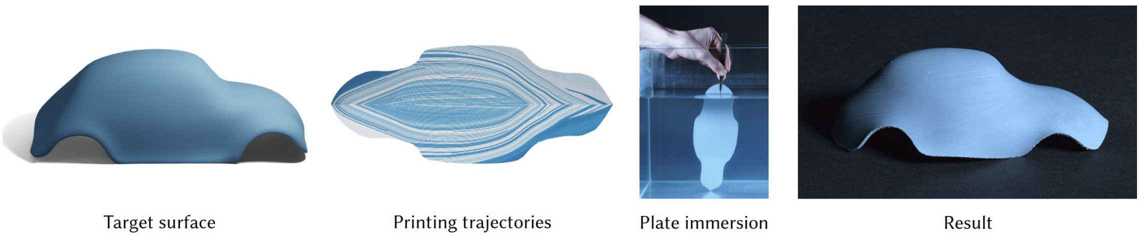
8.4 Shrink & Morph: 3D-printed self-shaping shells actuated by a shape memory effect

Participants: David Jourdan, Pierre-Alexandre Hugron, Camille Schreck, Jonàs Martínez, Sylvain Lefebvre.

We developed a computational framework for optimizing the internal structure of 3D printed plates such that they morph into a desired freeform shell when heated. This exploits the shrinkage effect of thermoplastics such as PLA, which store internal stresses along the deposition directions. These stresses get released when the material is heated again above its glass transition temperature, causing an anisotropic deformation that induces curvature.

Our inverse design method takes as input a freeform surface and finds an optimized set of deposition trajectories in each layer such that their anisotropic shrinkage deforms the plate into the prescribed surface geometry. We optimize for a continuous vector field that varies across the plate and within its thickness. The algorithm then extracts a set of deposition trajectories from the vector field in order to fabricate the flat plates on standard FFF printers. We validate our algorithm on freeform, doubly-curved surfaces.

This paper was published in TOG and presented at SIGGRAPH Asia 2023 [10] and received the Honorable Mention, which was awarded to the top 5% of the papers presented there. Code is available on github.



8.5 Curl Noise Jittering

Participants: Andreas Bærentzen, Jeppe Revall Frisvad, Jonàs Martínez.

In collaboration with DTU (Technical University of Denmark) researchers, we proposed an implicit method for generating blue noise point sets. Leveraging the volume-preserving nature of curl noise vector fields, we demonstrated that jittering, viewed as moving points along vector field streamlines, maintains well-separated points. This jittering also significantly diminishes anisotropy originating from regular lattices. The volume preservation and anisotropy reduction combination effectively transforms a regular lattice into a point set with blue noise properties. Our method, requiring no precomputation of the point set, proves valuable when an arbitrarily large set of points with blue noise properties is essential. We compared our approach to jittering-based and other blue noise point set generation methods. Additionally, we showcased curl noise jittering applications in two and three dimensions.

This work was published in the conference proceedings of Siggraph Asia 2023 [12] and the code is available on github.

8.6 Forward inclusion functions for ray-tracing implicit surfaces

Participants: Melike Aydinlilar, Cédric Zanni.

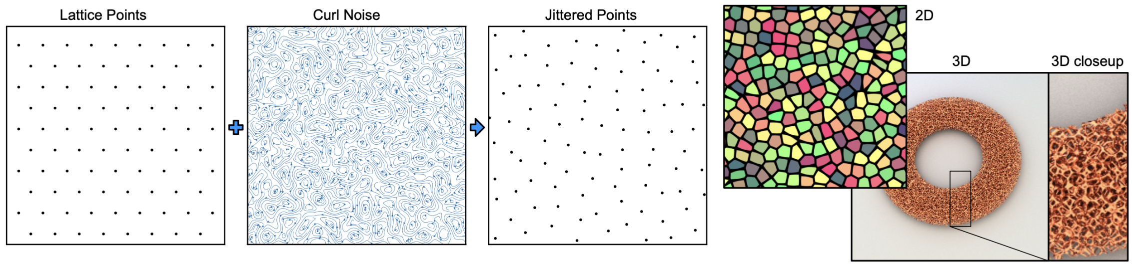


Figure 5: Points on a lattice are displaced by advecting them along a curl noise vector field. It is possible to efficiently find the closest jittered point to a given query point, and the jittered points have blue noise properties. The jittered points can be used for sampling, procedural texturing, or defining cellular materials (in 2D or 3D). The images on the right show a procedural texture based on Worley noise and a copper foam generated from our curl noise jittered points.

Using Lipschitz bounds as linear inclusion functions, we show that both Lipschitz-based ray-tracing and bottom-up inclusion functions can be used together in the same framework. We propose asymmetrical forward inclusion functions that are exact at the query point and can better encode the function's behavior on a given interval; therefore well suited for iterative processing. We show how to derive the linear and quadratic versions of these inclusion functions either by bounding the derivatives or building bottom-up inclusion functions and combining these two. We show our results on density fields defined from point primitives with compactly supported kernels and Gaussian kernels as well as Hermite radial basis functions. We demonstrate that our method provides noticeable improvement for grazing rays and transparent rendering.

This work was published in the conference proceedings of SMI 2023 [7], it was also presented at JFig 2023.

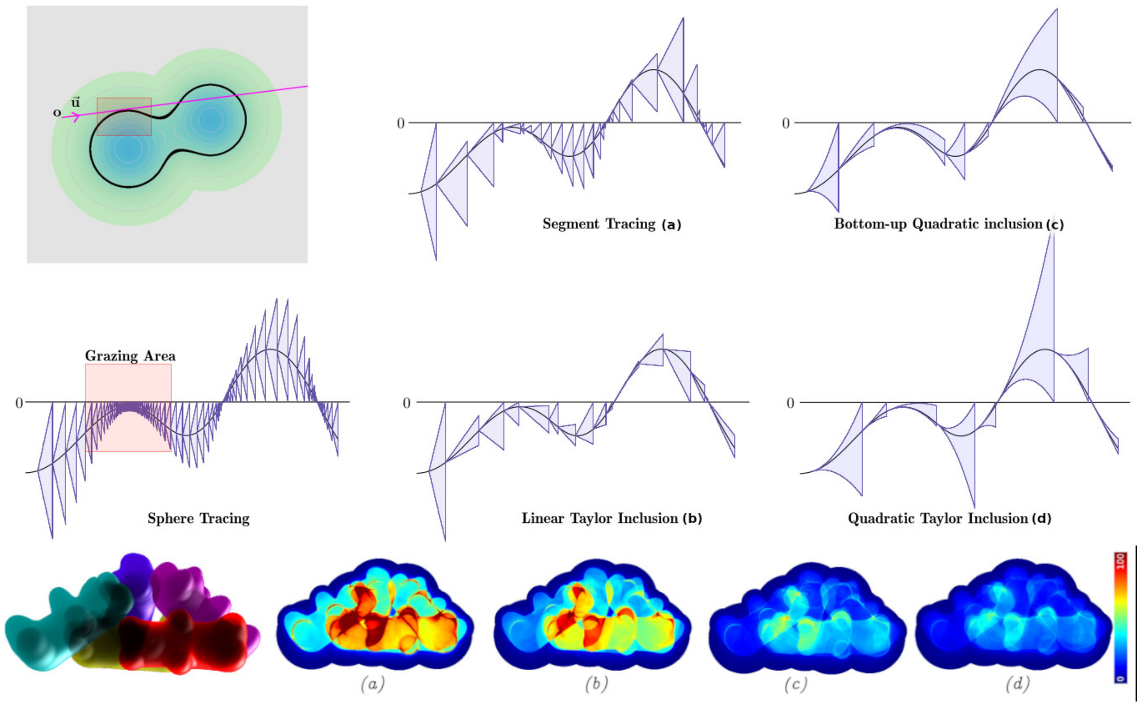


Figure 6: Comparison of the various proposed forward asymmetric bounds (b,c,d) with state of the art segment-tracing algorithm (a). Top: bounds computed along a given view ray. Bottom: number of bound evaluations per rays.

9 Bilateral contracts and grants with industry

9.1 Bilateral contracts with industry

Partnership with AddUp

Participants: Sylvain Lefebvre.

- Company: AddUp.
- Duration: Started in 2019.
- Abstract: AddUp 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. This partnership continued to develop in 2023.

Other industrial partnership

Participants: Sylvain Lefebvre, Salim Perchy.

- Company: (confidential)
- Duration: 2023.

10 Partnerships and cooperations

10.1 International research visitors

Other international visits to the team

Participants: Sylvain Lefebvre.

Emilio Ottonello

Status PhD student

Institution of origin: Italian Institute of Technology (IIT)

Country: Italy

Dates: October 2023 to March 2024

Context of the visit: Research on non-planar additive manufacturing.

Mobility program/type of mobility: research stay.

10.2 European initiatives

Participants: Sylvain Lefebvre, Pierre-Alexandre Hugron, Salim Perchy.

- Acronym: KARST.
- Title: KARST: Predicting flow and transport in complex Karst systems
- Duration: 2023-2028
- Coordinators: Benoit Noetinger (IFPEN, France), Bojan Mohar (Ljubljana University, Slovenia), Philippe Renard (Université de Neuchâtel, Switzerland), Marco Dentz (IDAEA-CSIC)
- Abstract: The MFX team participates to the ERC synergy KARST (ERC-KARST-101071836) as a helping research partner. The project started in May 2023. Our role is to assist with the research realting to additive manufacturing in the experimental study of karst systems.

10.3 National initiatives

ANR JCJC IMPRIMA

Participants: Sylvain Lefebvre, Cédric Zanni, Melike Aydinlilar, Nathaniel Seyler.

- Acronym: IMPRIMA.
- Title: Implicit modeling for additive manufacturing.
- Duration: 2019-2023.
- Coordinator: Cédric Zanni.
- Abstract: This project seeks to explore novel implicit representations to provide a unified approach for the modeling and slicing of both macro geometry, microstructures, and gradient of material. Additionally, this research aims to 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.

  Our latest results on the robust visualization of implicit surfaces has lead to a publication on opaque and transparent rendering [7] as well as a presentations to SMI 2023 and JFig 2023. The project ended in March 2023.

ANR MultiForm

Participants: Cédric Zanni.

- Acronym: MultiForm.
- Title: Multivariate Implicit Function defOrmation.
- Duration: 2023-2026.
- Coordinator: Loïc Barthe.
- Partners: Université Paul Sabatier, Ecole Polytechnique

- Abstract: This project aims at developing theoretical aspects of 3D field functions in computer graphics: 3D animation and the representation of complex multi-material virtual objects. An innovative aspect is the study of multivalued field functions and their deformations in this context. Practically, it aims at providing more efficient new solutions for both the deformation of animated 3D objects with collisions, and the representation of complex structures composed of several materials such as organic (muscular, bones, soft tissues) or liquid/solid structures (as a lava flow). The final goal being the deformations with collisions of these complex structures.

  The project started in September 2023.

10.3.1 Inria

Inria Exploratory Action CONTINUA

Participants: Jonàs Martínez, Luis Mollericon.

- Acronym: AEx CONTINUA.
- Title: Continuous deposition of paste-like materials.
- Duration: 2022-2026.
- Coordinator: Jonàs Martínez.
- Abstract: Additive Manufacturing (AM) using paste-like materials such as clay or silicon enables the construction of large-scale structures but poses significant challenges for intricate geometries. During the manufacturing process, there is a heightened risk of structural collapse under gravity, leading to defects caused by repeated interruptions in extrusion flow. Previous efforts have primarily focused on simpler structures, failing to harness the full potential of AM. AEx CONTINUA aims to explore the realm of manufacturable deposition paths to empower the Additive Manufacturing of large-scale, complex structures, addressing the inherent challenges and pushing the boundaries of AM capabilities.

Inria Challenge DORNELL

Participants: Sylvain Lefebvre, Pierre-Alexandre Hugron, Camille Schreck, David Jourdan.

- Acronym: DORNELL
- Title: A multimodal, shapeable haptic handle for mobility assistance of people with disabilities.
- Duration: 2022-2026.
- Coordinator: Marie Babel.
- Partners: Inria MFX, POTIOC,
- Abstract: While technology helps people to compensate for a broad set of mobility impairments, visual perception and/or cognitive deficiencies still significantly affect their ability to move safely and easily. DORNELL proposes an innovative multisensory, multimodal, smart haptic handle that can be easily plugged onto a wide range of mobility aids. Specifically fabricated to fit the needs of a person, it provides a wide set of tactile sensations in a portable and plug-and-play format – bringing haptics in assistive technologies all at once.

10.4 Regional initiatives

Jonàs Martínez received funding for a half-PhD scholarship in the context of his research on optimizing shapes for continuous deposition (Dispositifs Projets doctoraux 2023).

11 Dissemination

11.1 Promoting scientific activities

General chair, scientific chair Jonàs Martínez was a co-chair of the Journées Françaises d'Informatique Graphique (jFIG 2023) in Montpellier.

Member of the conference program committees

- Jonàs Martínez was part of the program committee of Pacific Graphics 2023 and Eurographics State-of-the-Art Reports 2023.
- Xavier Chermain was a technical communications and posters committee member of SIGGRAPH Asia 2023.
- Xavier Chermain was a program committee member of the Journées Françaises d'Informatique Graphique (jFIG 2023).
- Camille Schreck was a short papers committee member of Eurographics 2023.
- Camille Schreck was a program committee member of Shape Modeling International (SMI) 2023.
- Camille Schreck was a technical communications and posters committee member of SIGGRAPH Asia 2023.
- Camille Schreck was a program committee member of the Journées Françaises d'Informatique Graphique (jFIG 2023).
- Cédric Zanni was a program committee member of Journées Françaises d'Informatique Graphique (jFIG 2023).
- Sylvain Lefebvre was a program committee member of SIGGRAPH 2023.
- Sylvain Lefebvre was a program commitee member of Eurographics 2024.
- Sylvain Lefebvre served on the advisory board of Eurographics 2024.

Reviewer

- Jonàs Martínez was reviewer for SIGGRAPH 2023, SIGGRAPH Asia 2023, and Eurographics 2023.
- Xavier Chermain was reviewer for Pacific Graphics 2023.
- Camille Schreck was reviewer for SIGGRAPH 2023, SIGGRAPH Asia 2023.
- Cédric Zanni was reviewer for SIGGRAPH 2023.
- Sylvain Lefebvre was reviewer for SIGGRAPH Asia 2023.
- Jonàs Martínez was reviewer for the journal Structural and Multidisciplinary Optimization (Elsevier) and Scientific Reports (Nature).

11.1.1 Invited talks

- Jonàs Martínez gave an invited talk at IUTAM Symposium on Ultralarge-scale topology optimization 2023 entitled "Procedural single scale structures for scalable dehomogenization".
- August 29, 2023: Xavier Chermain gave an invited talk in Inria team MANAO, Bordeaux.
- June 14, Sylvain Lefebvre gave an invited talk at the "Journées du réseau des mécaniciens CNRS",
- February 6, Sylvain Lefebvre gave an invited course at Ecole Polytechnique (Paris), hosted by Etienne Reyssat (together with Corentin Coulais).
- February 7, Sylvain Lefebvre gave an invited talk (*Conférence Expérimentale*, together with Corentin Coulais) at ESPCI (Paris).

11.1.2 Scientific expertise

Jonàs Martínez was an external expert for ETH Zürich.

11.2 Teaching - Supervision - Juries

11.2.1 Teaching

- Master: Jonàs Martínez, Introduction to data parallelism, 30h ETD, Université de Lorraine, France.
- Master: Jonàs Martínez, Advanced machine architectures (GPU), 25h ETD, Télécom Nancy, France.
- Preparatory classes: Xavier Chermain, Nouveaux paradigmes de programmation et science des données, 64h ETD, prépa INP Nancy.
- Master: Camille Schreck, Introduction to 3D Graphics, 26h ETD, Telecom Nancy, France.
- Master: Camille Schreck, 3D Graphics and Parallelism, 12h ETD, ENSG Nancy, France.
- Master: Cédric Zanni, Software Engineering, 31.5h ETD, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Introduction to C/C++, 54h ETD, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Techniques for video game programming, 27h ETD, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, ARTEM Game Lab, 22h ETD, M1, École des Mines de Nancy, France.
- Master: Cédric Zanni, Projets Département Informatique, 10h 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, Algorithms for additive manufacturing, 12h ETD, Master M2 AVR, Nancy, France.
- Master: Sylvain Lefebvre, Hardware design on FPGA, 12h ETD, Telecom Nancy, France.
- License: Cédric Zanni, Outils informatique, 16h ETD, L3, École des Mines de Nancy, France.
- License : Cédric Zanni, Introduction to Computer Science, 31.5h ETD, L3, École des Mines de Nancy, France.
- License LP AFTER: Sylvain Lefebvre, 3D printing with IceSL, 6h ETD, Université de Lorraine, France
- License FACDR: Sylvain Lefebvre, 3D printing with IceSL, 6h ETD, Université de Lorraine, France
- License: Pierre-Alexandre Hugron, Introduction to 3D printing, École des Mines, 6h ETD

11.2.2 Supervision

- Defended PhD : Melike Aydinlilar, Implicit modeling for additive manufacturing, started in 2019, advisors: Sylvain Lefebvre, Cédric Zanni.
- Ph.D. in progress: Luis Mollericon Titirico, Continuous deposition of paste-like materials, advisors: Jonàs Martínez, Sylvain Lefebvre.
- Internship: Morgan Mellinger, algorithms to compute spiral trajectories for additive manufacturing, Université de Lorraine, advisors: Jonàs Martínez, Pierre-Alexandre Hugron, Sylvain Lefebvre.
- Research initiation: Paul Devilliers, Zinedine Ait-Aider, Matthieu Amet, M1 Université de Lorraine. The objective was to conduct experimentations on chocolate 3D printing. Advisor: Pierre-Alexandre Hugron.

11.2.3 Juries

Jonàs Martínez was a reviewer for the PhD thesis of Erik Albert Träff (Technical University of Denmark). Camille Schreck was part of the mid-thesis committee of Nicolas Rosset.

11.3 Popularization

11.3.1 Internal or external Inria responsibilities

Sylvain Lefebvre was head of the Commission des Développements Technologiques (CDT).

11.3.2 Articles and contents

Inria published an article about our appearance fabrication article [8].

11.3.3 Events

- MFX organized a booth at 3DPrint Paris (11-12 October), where it jointly presented research results with the Ofast3D and DORNELL projects teams. Pierre-Alexandre Hugron, David Jourdan, Salim Perchy and Sylvain Lefebvre were present.
- MFX did an IceSL presentation and demonstration at the Inria booth, Vivatech, Paris, 14/06/23. Participant: Nathaniel Seyler and Pierre-Alexandre Hugron.

11.3.4 Interventions

- 19/04/2023: Xavier Chermain gives a presentation for the students of the Institut des hautes études pour la science et la technologie (IHEST)
- 25/04/2023: Pierre-Alexandre Hugron did an IceSL presentation during Fabrikathon at IUT Charlemagne.
- 29/09/2023: Xavier Chermain, Cédric Zanni and Pierre-Alexandre Hugron were presenters at the European Researchers' Night 2023 at Metz.

12 Scientific production

12.1 Major publications

[1] M. Aydinlilar and C. Zanni. 'Fast ray tracing of scale-invariant integral surfaces'. In: *Computer Graphics Forum* 40.6 (Sept. 2021), pp. 117–134. DOI: 10.1111/cgf.14208. URL: https://hal.inria.fr/hal-03169283.

[2] J. Dumas, J. Hergel and S. Lefebvre. 'Bridging the Gap: Automated Steady Scaffoldings for 3D Printing'. In: *ACM Transactions on Graphics*. ACM Transactions on Graphics (TOG) - Proceedings of ACM SIGGRAPH 2014 33.4 (July 2014), 98:1–98:10. DOI: 10.1145/2601097.2601153. URL: https://hal.inria.fr/hal-01100737.

[3] J. Etienne, N. Ray, D. Panozzo, S. Hornus, C. C. Wang, J. Martínez, S. Mcmains, M. Alexa, B. Wyvill and S. Lefebvre. 'CurviSlicer: Slightly curved slicing for 3-axis printers'. In: *ACM Transactions on Graphics* 38.4 (Aug. 2019), pp. 1–11. DOI: 10.1145/3306346.3323022. URL: https://hal.science/hal-02120033.

[4] J. Martínez, J. Dumas, S. Lefebvre and L.-Y. Wei. 'Structure and appearance optimization for controllable shape design'. In: *ACM Transactions on Graphics* 34.6 (Nov. 2015), p. 12. DOI: 10.1145/2816795.2818101. URL: https://hal.inria.fr/hal-01240642.

[5] J. Martínez, S. Hornus, H. Song and S. Lefebvre. 'Polyhedral Voronoi diagrams for additive manufacturing'. In: *ACM Transactions on Graphics*. Proceedings of SIGGRAPH 2018 37.4 (Aug. 2018), p. 15. DOI: 10.1145/3197517.3201343. URL: https://hal.inria.fr/hal-01697103.

[6] T. Tricard, V. Tavernier, C. Zanni, J. Martínez, P.-A. Hugron, F. Neyret and S. Lefebvre. 'Freely orientable microstructures for designing deformable 3D prints'. In: *ACM Transactions on Graphics* (Dec. 2020). DOI: 10.1145/3414685.3417790. URL: https://hal.inria.fr/hal-02524371.

12.2 Publications of the year

International journals

[7] M. Aydinlilar and C. Zanni. 'Forward inclusion functions for ray-tracing implicit surfaces'. In: *Computers and Graphics* (June 2023). DOI: 10.1016/j.cag.2023.05.026. URL: https://inria.hal.science/hal-04129922.

[8] X. Chermain, C. Zanni, J. Martínez, P.-A. Hugron and S. Lefebvre. 'Orientable Dense Cyclic Infill for Anisotropic Appearance Fabrication'. In: *ACM Transactions on Graphics* 42.4 (1st July 2023), p. 13. DOI: 10.1145/3592412. URL: https://hal.science/hal-04129173.

[9] M. Freire, M. Bhargava, C. Schreck, P.-A. Hugron, B. Bickel and S. Lefebvre. 'PCBend: Light Up Your 3D Shapes With Foldable Circuit Boards'. In: *ACM Transactions on Graphics* (2023). DOI: 10.1145/3592411. URL: https://inria.hal.science/hal-04129354.

[10] D. Jourdan, P.-A. Hugron, C. Schreck, J. Martinez and S. Lefebvre. 'Shrink & Morph: 3D-printed self-shaping shells actuated by a shape memory effect'. In: *ACM Transactions on Graphics* 42.6 (Dec. 2023). DOI: 10.1145/3618386. URL: https://inria.hal.science/hal-04252044.

[11] S. v. '. Sant, P. Thakolkaran, J. Martínez and S. Kumar. 'Inverse-designed growth-based cellular metamaterials'. In: *Mechanics of Materials* 182 (May 2023), p. 104668. DOI: 10.1016/j.mechmat.2023.104668. URL: https://inria.hal.science/hal-04091373.

International peer-reviewed conferences

[12] J. A. Baerentzen, J. R. Frisvad and J. Martínez. 'Curl Noise Jittering'. In: 16th ACM Conference and Exhibition on Computer Graphics and Interactive Techniques (SIGGRAPH Asia 2023). Sydney, Australia, 12th Dec. 2023. DOI: 10.1145/3610548.3618163. URL: https://hal.science/hal-04227903.

Reports & preprints

[13] C. Zanni. *Synchronized-tracing of implicit surfaces*. 17th Apr. 2023. URL: https://inria.hal.science/hal-04071989.