Report from Dagstuhl Seminar 18431

Computational Aspects of Fabrication

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 18431 "Computational Aspects of Fabrication".

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1 Executive Summary

Marc Alexa
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As manufacturing goes digital, we are facing a fundamental change in the workflow of fabrication. While access to advanced digital fabrication and 3D-printing technology becomes ubiquitous and provides new possibilities for fabricating complex, functional, multi-material objects with unconventional properties, its potential impact is currently limited by the lack of efficient and intuitive methods for content creation. Existing tools are usually restricted to expert users, have been developed based on the capabilities of traditional manufacturing processes, and do not sufficiently take fabrication constraints into account. Scientifically, we are facing the fundamental challenge that existing simulation techniques and design approaches for predicting the physical properties of materials and objects at the resolution of modern 3D printers fail to scale well with possible object complexity.

To achieve significant progress, we need a deep understanding of interdisciplinary fundamentals: Shape, Appearance of Shape and Materials, Validated Simulation, and Engineering Design. The purpose of this Dagstuhl Seminar is to bring together leading experts from academia and industry in the area of computer graphics, geometry processing, mechanical engineering, human-computer interaction, material science, and robotics. The goal is to address fundamental questions and issues related to computational aspects of fabrication, build bridges between related fields, and further pioneer this area.

There has been a considerable growth in the number of articles treating aspects of computational fabrication, scattered across multiple disciplines and journals. In this seminar we gathered together these various threads and described the computational accomplishments and outstanding challenges. Researchers from different communities analyzed which existing fabrication workflows could benefit most from computation and identify novel application domains, with the aim of cross-fertilizing ideas between disciplines. The main goal of this seminar was identifying and reporting common grand challenges and developing a roadmap for addressing them. Additionally, the seminar seeked to discuss and establish standards and best practices for sharing research results, code, and hardware prototypes, facilitating reproducibility and reusability of results among disciplines. An important aspect of this was to analyze teaching and learning needs for new students in the field, and coordinating the development of teaching material.

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3 Overview of Talks

3.1 Computational Nanofabrication

Thomas Auzinger (IST Austria – Klosterneuburg, AT)

Joint work of Thomas Auzinger, Wolfgang Heidrich, Bernd Bickel
Main reference Thomas Auzinger, Wolfgang Heidrich, Bernd Bickel: "Computational design of nanostructural color for additive manufacturing", ACM Trans. Graph., Vol. 37(4), pp. 159:1–159:16, 2018.
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Multiphoton lithography – also known as Direct Laser Writing – provides an accessible nanofabrication method that resembles the workflow of 3D printing. As it solidifies the photoresist only in the focus region of the femtosecond-pulsed laser beam, it allows nearly unrestricted freeform writing of nanostructures. We utilized this fabrication method to create structural colorization of glass surfaces by transparent nanostructures. The structures themselves were discovered by a fully automatic inverse design method based on electromagnetic simulation. Efforts by other groups used Direct Laser Writing to create nanolattices, whose specific strength surpases that of steel, as well as microrobots, microneedles, and cell cages.

3.2 Fine Art Appearance Fabrication

Vahid Babaei (MPI für Informatik – Saarbrücken, DE)

Reproduction of fine art objects has been a topic of interest for many decades, pursued by many technologies. In general, the results have not been satisfactory as the quality bar is very high for this particular application. Multi-material 3D printing is the latest technology and a new hope for a physical reproduction with archival quality. Among fine art artifacts, we find paintings as an excellent case-study due to the rich appearance, unique challenges and rather convenient fabrication. Multi-material 3D printing is not only able to reproduce the fine 3D geometry present in many forms of paintings, but also other appearance attributes, such as spectral color and gloss. In this talk, I discuss the opportunities enabled by 3D printing for fine art reproduction. In contoning, for example, one can eliminate the traditional halftoning artifacts using the inherent ability of 3D printers in layering inks on top of each other. Using the same property of 3D printers, I show that the spectral gamut of a 3D printer can exceed the one of a 2D printer significantly thereby enabling truly spectral reproduction of fine art. I also speak about challenges where aside from computational problems, such as accurate volumetric prediction of appearance, an open hardware platform that gives the possibility of tuning both machines and materials is indispensable.

3.3 Fabrication-aware design: Where we are? Where are we going?

Amit Haim Bermano (Princeton University, US)

We have recently published a state-of-the-art report and a book about the advances made in computational fabrication by the computer graphics community. By drawing conclusions from this work, I would like to discuss one of the pressing issues I believe should be investigated in the near future in the context of fabrication-aware design: Design through objectives, instead of geometry, using a hierarchical, modular, representation.

3.4 Computational Design of Physical Characters and Structures

Moritz Bächer (Disney Research – Zürich, CH)

Stimulated by advances in manufacturing, fabrication-oriented design has gained an increasing level of interest from the graphics community. With modern manufacturing technologies, we can build physical characters and large-scale structures of nearly unbounded complexity by shifting the design burden to computational approaches.

In a first part, I will talk about a technique that aids with the design and fabrication of elastically-deforming kinetic wire characters. Our technique takes as input a network of curves or a skeletal animation, then estimates a cable-driven, compliant wire structure which matches user-selected targets or keyframes as closely as possible. To enable large local deformations, we shape wire into functional spring-like entities, optimizing their stiffness. We use consumer-grade hardware to fabricate our optimized designs.

In a second part, I will talk about a worst-case optimization of structures that are weak in tension. I will introduce a technique to derive distance metrics from failure criteria, formulating a stress objective that accounts for asymmetries in the tensile and compressive strength of common build materials. Parameterizing uncertainties in load cases, we introduce a formulation, optimizing structures under worst-case loads. I will show several optimized structures, tailored for manufacturing on large-scale binder jetting technologies.

3.5 Meaningful Applications of 3D Printing. Key computational components for success.

Sabine Demey (Materialise HQ – Leuven, BE)

In Industry 4.0, the reasons why people turn to 3D Printing are still largely the same as before. The reasons can be summarized as Design, Cost and Time: Freedom of design, function before form, affordable small series, no tool-making required, faster design iterations, faster time-to-market, etc... People increase expectations though. Products should be highly personalized, be of high quality, with many details, in multiple materials, etc. and the higher complexity is expected to be supported at no added cost. In support of this complex journey from idea to 3D printed product, software has enormous computationally powerful algorithms under the hood and the need for these algorithms is increasing more than ever. The AI hype is also contributing to this. I will bring you in touch with a variety applications using 3D printing to create a better and healthier world. These applications will reveal one by one the need for powerful computations.

3.6 The Design and Fabrication of Smart Textiles

Laura Devendorf (University of Colorado – Boulder, US)

The term "smart textiles" describes fabrics with sensing and actuation capabilities integrated into their structure at the yarn-level. While a consumer-level infrastructure for the rapid fabrication of textiles is emerging, we have a lack of design tools to effectively leverage this infrastructure for new application domains. This talk will describe the pipeline of textiles fabrication, the structural properties of woven fabrics that open up new spaces for computational design, and how textiles might require new forms of human machine collaboration.

3.7 AM representation that enables design

Georges Fadel (Clemson University – Clemson, US)

Much of the focus on representation for additive manufacturing has been on the format that enables 3D printers to efficiently and reliably translate the designers' creation into a solid object. The STL format has been a significant component of the success of the AM, but has also been recognized to have shortcomings, and researchers have proposed new formats such as AMF. These formats however, are not adequate for the designer who seeks to take advantage of the full potential of AM, specifically the ability to modify the shape and topology, to include material variability and anisotropy. Once the design is done, existing formats would allow the 3D printer to print it, but since CAD tools are surface based representations that do not provide this flexibility, researchers keep trying to find alternate approaches. The voxel representation may be adequate again for the interface to the printers, but how can it be used in the design? Topology optimization and a two level approach may be appropriate, the lower level elements being of the scale of voxels. However, traditional homogenization approaches are limiting, and do not provide the designer with the full flexibility needed to design and manufacture novel artifacts since they depend on full Y-Periodicity and on a small size cell as compared to the design space in all directions. We need a representation, which provides the designer with a volumetric design tool that allows design for additive manufacturing.

3.8 Human-Centered Interfaces for Autonomous Fabrication

Madeline Gannon (Atonaton – Pittsburgh, US)

This talk discusses the potentials and merits of fabrication machines becoming collaborative companions in computational fabrication processes. I highlight several technical challenges of bypassing computers to directly engage with fabrication machines. I then share my recent, ongoing research into fluid, intuitive interfaces for industrial robots. As one of our most versatile and adaptable fabrication machines, industrial robots are a reliable and agnostic hardware platform for several additive and subtractive processes. The goal of this research is to demonstrate novel relationships between people and machines that can augment our existing computational design and fabrication processes in fruitful ways.

3.9 New computational tools to support Design for Additive Manufacturing (DfAM) in the early stages of the Product Development Process

Serena Graziosi (Polytechnic University of Milan, IT)

The rapid development of additive manufacturing technologies is continuously providing new stimuli to creative people and industries. From modelling and printing complex geometries, their interest has now moved towards the possibility to create complex and smart systems by mimicking, replicating and eventually extending the complexity of natural systems. However, to reach such a challenging target, designers need support in understanding and mastering the complexity of the phenomena and thus of the aspects determining the system behaviour and architecture. Most of the current design tools were conceived to support detailed design activities and are not effective in supporting designers in such an exploration which should take place during the concept design phase of the product development process. Indeed, it is during this phase that new ideas are generated, and designers have enough time to investigate how to exploit the potentialities of additive manufacturing technologies in their products, i.e., how to Design for Additive Manufacturing (DfAM). This talk aims to stimulate the development of new computational tools for the concept design phase. These tools should help designers to understand the system behaviour in real-time through quick and easy to set-up simulations, even simplified ones, for example by combining 3D modelling with multiphysics analyses, and by letting designers make informed decisions.

3.10 Taking out the Hard Edges: New Printers and Processes for Fabricating Soft Materials

Scott Hudson (Carnegie Mellon University – Pittsburgh, US)

Much of what I do involves building unique new 3D printers and other fabrication machines, and I have been particularly interested in expanding our ability to create soft objects. Soft objects have unique advantages, particularly in objects used by humans, and yet we have comparatively few ways of digitally fabricating them. In this talk I will consider several machines which work with fibers as a material, such as a 3D printer which prints in needle felted yarn, and printing using electrospun fibers, as well as a new inexpensive and accessible silicone rubber printer.

3.11 Robust Geometry Processing: the Life Cycle of a Messy Shape

Alec Jacobson (University of Toronto, CA)

I will discuss my vision for a robust geometry processing pipeline. I propose that we reject the traditional "garbage in, garbage out" policy. Instead, we should return to first principles and hunt for solutions that adapt and gracefully degrade in the presence of messy inputs. I will highlight a few very recent successes (winding numbers for inside/outside classification, Boolean operations on triangle meshes, and tetrahedral volumetric meshing). I will emphasize their importance to computational fabrication via applications to 3D printed movies, stop motion and generalized Matryoshka dolls.

3.12 A Software Platform for Algorithmic Design

Lin Sebastian Kayser (Hyperganic Technologies AG – München, DE)

Five years ago I started a company called Hyperganic with the goal to enable algorithmic design of highly complex objects. I'd like to share the progress that we've made and show how using our voxel-based approach, we can break down the entry barriers of generative design applications, by making it very easy to create even complex algorithms and solutions.

3.13 Human Perception of 3D Shapes

Manfred Lau (City University – Hong Kong, HK)

In this talk, I will describe two projects that look at the human perceptual properties of 3D shapes. The first is tactile saliency. While there has been previous research in the area of visual saliency, both for images and for 3D meshes, we introduce the concept of tactile mesh saliency. For example, a point on a 3D mesh is more tactile salient than another if it is more likely to be grasped. I describe the data collection process and the learning method for computing tactile saliency. The second perceptual property is the softness of 3D meshes, where we look at how humans perceive the softness of the surface of virtual meshes. We take a similar approach as in the first project to compute softness. I will also discuss applications of these perceptual properties including for fabrication and describe potential challenges for the future.

3.14 Fused filament fabrication of parts with gradients of properties

Sylvain Lefebvre (LORIA & INRIA – Nancy, FR)

In this presentation I describe some of our ongoing research to grade properties within parts, such as elasticity and color. I will first discuss how to represent complex infill structures in a compact, efficient manner using pixel shaders written in the OpenGL shading language. These shaders can be provided directly to our slicing software (IceSL) which uses them to produce toolpaths within parts. I will then describe ongoing work on micro-layering to produce color gradients using FDM printers. Finally, I will discuss some still open challenges regarding support structures and surface finish.

3.15 Designing Volumetric Truss Structures

David I. W. Levin (University of Toronto, CA)

Voxels, voxels everywhere has been the long standing mantra of computational design algorithms. This seems at odds with output of such procedures which are typically well defined, low dimension primitives such as curves. In this talk I will discuss the implications of this representational conflict as well as detail a new voxel free method for optimal truss generation for 3D printing. I'll conclude with thoughts on future problems in computational design.

3.16 Appearance and Interiors Optimization for Extrusion-based Fabrication

Lin Lu (Shandong University – Qingdao, CN)

My talk basically includes two parts, appearance and interiors optimization. First, I share some attempts on printing complex shapes. Different shape classes such as hair/fibers and architectural models have driven research toward class-specific solutions. 3D trees are an especially challenging case for 3D manufacturing. They consist of non-volumetric patch leaves, an extreme amount of small detail often below printable resolution and are often physically weak to be self-sustainable for single material. I describe the knowledge based optimizations in terms of both geometric and physical constraints and show 3D printed trees. Then I discuss the defects of extrusion based fabrication, e.g, FDM, and take an image carving example to show the details adaption results based on the physical constraints. In the second part, I talk the interiors in closed-cell and open-cell structures and discuss the advantages and disadvantages of these structures in terms of manufacturing feasibilities and applications. Challenges remaining in the mentioned problems are discussed in the end.

3.17 Procedural and stochastic microstructures for AM

Jonas Martinez-Bayona (INRIA Nancy – Grand Est, FR)

Additive Manufacturing (AM) technologies are now capable of fabricating microstructures at the scale of microns, therefore enabling to precise control of the macroscopic physical behavior. This control empowers a wide range of industrial applications by bringing high-performance customized materials. Microstructures for AM will play a decisive role in the factory of the future, but several challenges remain aside. In this talk we consider procedural, stochastic, and fabricable microstructures, with a controlled macroscopic physical behavior. As a result of their stochastic nature such microstructures afford for free grading and embedding of microstructures into objects, hence avoiding the limitations imposed by periodic structures.

3.18 Machine Learning for AM Monitoring

Sara McMains (University of California – Berkeley, US)

I describe a machine learning based approach to in-situ quality monitoring for Selective Laser Melting (SLM). Our collaborators at Lawrence Livermore National Laboratory modified the SLM apparatus to include a high-speed camera that follows the mirror/galvanometer-controlled path of the scanning laser to gather in-situ video data of the melt pool. After fusing separated experimental tracks and removing unfused powder, a height field is obtained (ex-situ) by scanning with a structured light microscope. Our two-stage height field segmentation algorithm classifies track, etch, & background pixels in order to automatically label 10-frame videos with track width (for regression training) and presence or absence of breaks (for classification training).

A CNN architecture whose hyperparameters are tuned for one modality successfully predicts both width and continuity.

3.19 Fabrication and 3D Modeling at Adobe

Radomir Mech (Adobe Inc. – San José, US)

In this talk I overviewed technologies that we have most recently developed and research direction that we are pursuing at Adobe Research. I showed a project on mapping 2D dielines to 3D folded geometry that can be used to place decals so that they show correctly on the folded object. The second project was on easy manipulation of 3D objects using handles based on wires created on salient features. In addition, I presented future directions in the area of 3D modeling: assembly based modeling, parametric modeling and ways to explore parametric space of 3D models.

3.20 Creation for everyone: Broadening participation, increasing accessibility, democratizing engineering, and other warm fuzzy goals

Ankur Mehta (University of California at Los Angeles, US)

Computational fabrication broadly aims to automate challenging design tasks in the process of creation. We can therefore use this to bring the act of creation to those with minimal access to resources, expertise, or background; I posit that this can provide the most significant benefit to society by incentivizing education in the demographics that most need it. We therefore need to consider extremely low cost manufacturing processes, accessible and intuitive design interfaces, and the needs and expectations of the target users. I show some initial work building on this motivation towards design automation for inexpensive paper-based robots.

3.21 From Material to Autonomy via Programmability

Shuhei Miyashita (University of York, GB)

Living systems in general feature a functionality to heal their structures when damaged while artificial systems do not. This is mainly because living systems are made in bottom-up, by protein molecules. Such self-assembly processes happen in a way that structures increase their dimensions; parts (e.g. amino acids) form one dimensional strings that are further reconfigured to a higher dimensional structures (e.g. 3D proteins). This talk presents heat-driven self-folding origami robots: the mechanism, capabilities, potential, and the limitation.

3.22 Materializing performance-driven form for architecture

Caitlin Mueller (MIT – Cambridge, US)

My research (digitalstructures.mit.edu) focuses on performance-driven design in architecture, often from the perspective of structural engineering, and how freedom of design expression and authorship can be reconciled with efficiency and related performance goals. A subset of this work relates to materialization, and specifically to tackling the geometric complexities that emerge from performance-driven design processes. While building-scale construction currently still favors standardization and regularity to an overwhelming degree, there is potential in the future to achieve performance-driven design complexity through new computationally driven methods for fabrication and assembly. In my talk, I'll discuss examples in 3D spatial extrusion, engineered timber, and reinforced concrete, all at architectural scale.

3.23 Rapidly Deployable Elastic Gridshells

Julian Panetta (EPFL – Lausanne, CH)

I will present a new approach for designing elastic gridshells where the deployed shape is encoded directly into the layout and cross section geometry of the beams. Traditional gridshells employ a regular grid layout that by itself has no knowledge of the target shape; the deployed shape is determined by what planar boundary curve is cut from this grid and how the beam endpoints on this boundary are moved to their target locations. This deformation causes each beam to buckle into a 3D curve, but the final shape that arises can depend on the order in which the endpoints are moved. Our work seeks to simplify the deployment process by designing spatially varying grids with a single easily actuated deployment path from the flat assembly configuration to a uniquely specified curved shape. I will present some examples that we have created and discuss some of the challenges of designing and robustly simulating these structures.

3.24 Design of Complex Assemblies

Mark Pauly (EPFL – Lausanne, CH)

Interlocking assemblies have a long history in the design of puzzles, furniture, architecture, and other complex geometric structures. The key defining property of interlocking assemblies is that all component parts are immobilized by their geometric arrangement, preventing the assembly from falling apart. Computer graphics research has recently contributed design tools that allow creating new interlocking assemblies. However, these tools focus on specific kinds of assemblies and explore only a limited space of interlocking configurations, which restricts their applicability for design.

In this talk, I will describe a new general framework for designing interlocking assemblies. The core idea is to represent part relationships with a family of base Directional Blocking Graphs and leverage efficient graph analysis tools to compute an interlocking arrangement of parts. This avoids the exponential complexity of brute-force search. The algorithm iteratively constructs the geometry of assembly components, taking advantage of all existing blocking relations when constructing successive parts. As a result, our approach supports a wider range of assembly forms compared to previous methods and provides significantly more design flexibility. We show that our framework facilitates efficient design of complex interlocking assemblies, including new solutions that cannot be achieved by state of the art approaches.

3.25 Rapid prototyping of rapid prototyping machines

Nadya Peek (University of Washington – Seattle, US)

Digital fabrication machines are becoming less expensive and therefore more accessible. However, they largely follow the same workflow: g-code moves a 3-axis gantry with a 3d print head or spindle. Custom digital fabrication machines enable diverse fabrication practices, including different kinematic models, different end effectors, and different user interactions. But building custom digital fabrication machines requires time and expertise. In this talk, I will present a variety of modular parts for machine building, including modular networked controllers, modular mechanical machine axes, and workflow composition software. Finally, I'll show how non-expert machine builders are able to construct lots of different kinds of machines using this modular machine infrastructure.

3.26 Molding is the new Black

Nico Pietroni (University of Technology – Sydney, AU)

While 3D printing technologies are becoming faster and more precise, classical manufacturing techniques remain the first choice for most industrial application scenarios. Industrial production is still largely dominated by casting techniques: casting scales well with the number of copies, supports a wide spectrum of materials, and ensures high geometric accuracy.

In this talk I will show recent advancement on geometry processing and shape analysis for the automatic design and fabrication of 3D printed molds. I will show the technical details and the effectiveness of new technologies that use 3D printing to automatise industrial production processes.

3.27 Mobile Fabrication

Thijs Roumen (Hasso-Plattner-Institut – Potsdam, DE)

We have gotten accustomed to mobile computing, whenever we encounter information problems, we solve them on the go. But when it comes to mechanical problems, we either just accept this or panic. Would it be possible to use the power of digital fabrication in that mobile context to solve our mechanical problems as we encounter them? I think so! In this talk, I will present the vision and challenges for making mobile fabrication a reality, I outline some of the current and future projects I am involved in to make mobile fabrication a reality and highlight my goal of forming a community of people to overcome these hurdles.

3.28 Toolpathing for 3D Printing

Ryan Schmidt (Gradientspace – Toronto, CA)

3D Printing is widely used in fabrication research and in practice, but the focus of most research is either at the level of geometry or machine. Comparatively little research targets the toolpathing algorithms that provide the interface between designs and robots. I will discuss how toolpathing is a major determinant of manufacturability, and that current toolpathing techniques leave much to be desired. Specific topics will include examples of novel design spaces exposed by small changes to the toolpathing pipeline, attempts to resolve assembly tolerances at the toolpath level, and potential directions for shape-aware toolpathing strategies.

3.29 Predictability and Robustness in Design for Additive Manufacturing (AM)

Carolyn C. Seepersad (University of Texas at Austin, US)

Additive manufacturing (AM) is making a profound impact on the way engineers realize customized parts, but fully realizing the manufacturing freedom afforded by AM requires some significant advances in engineering design methods and tools. For some additive manufacturing applications, simulation-based design tools may be required to explore a hierarchy of features, ranging in size from microns to meters. When these features are fabricated, however, AM systems typically induce significant deviations from intended geometry and mechanical performance. Designers need comprehensive statistical models that characterize this variability. Furthermore, they need design tools that use these models to provide real-time feedback on the constraints and process-structure-property relationships relevant to specific AM technologies, and this Design-for-AM feedback is needed during the design process, rather than at the end. To address these challenges, a design exploration approach has been established for creating inverse maps of promising regions of a hierarchical structural/material design space. The approach utilizes Bayesian network classifiers for identifying sets of promising solutions to a materials design problem by efficiently utilizing information gained from simulations, experiments, and/or expert knowledge. It also makes use of statistical characterization of geometric features and material properties to identify robust designs. The capabilities of the approach are demonstrated by applying it to the hierarchical design of negative stiffness metamaterials for energy absorption applications.

3.30 4D Printing: The new frontier

Kristina Shea (ETH Zürich, CH)

4D printing considers the 3D printing of designs with active materials so that they can function as machines, e.g. providing locomotion or reconfiguring their shape, without the need for drop-in components or 3D printing of conductive elements. The fourth dimension in 4D printing is time. This talk highlights our research on novel designs for 3D printed, tunable, multi-stable structures and an untethered swimming robot both of which activate through changes in temperature using a combination of shape memory polymers and bi-stability. Finally, computational design problems and results are shown for computing and optimizing 3D printed, shape morphing 2.5D and 3D structures activated through bi-stability, shape memory polymers and pneumatics.

3.31 Design of Meta-materials for Digital Fabrication

Melina Skouras (INRIA – Grenoble, FR)

Meta-materials are materials that owe their bulk properties primarily from their geometric structure. Designing meta-materials with extremal properties is a challenging task and is usually done by hand. In this talk, I will present a pipeline to (1) automatically characterize the range – or gamut – of mechanical properties that can be achieved by assemblies of 3D-printed voxels of base materials, (2) automatically identify microstructures sharing common geometric traits and cluster them into distinct families, and (3) to generate parametric templates for each family allowing to represent the microstructures at arbitrary resolutions.

3.32 Experiments in Extrusion-based Clay Printing

Bernhard Thomaszewski (Université de Montréal, CA)

Extrusion-based clay printing is an accessible technology for additive manufacturing of customized ceramics. There are, however, several aspects which make this process challenging.

Unlike conventional thermoplastics, clay is a viscoplastic material that remains comparatively soft throughout printing. Its limited load bearing capacities can lead to deformations or even collapse during printing. A second challenge is that discontinuities in the print paths lead to artifacts that quickly amplify and lead to failure. This is particularly problematic when generating support structures, which typically rely on disconnected paths. Finally, uneven drying of the model after printing can lead to large deformations and even fracture. In this talk, I described these challenges in more detail and indicated some avenues for possible solutions.

3.33 Making 3D Prints more Functional using Electronics and Machine Learning

Nobuyuki Umetani (AUTODESK Research – Toronto, CA)

In this talk, I introduce our recent attempts to enhance the functionality of the 3D prints. First, I talk about our technique to firmly mount electronic circuits on the top of the 3D prints to add various modalities such as light, sound and movements. Then, I talk about the use of the machine learning in the context of the 3D shape generation and aerodynamically efficient shape design. Finally, I discuss the challenges in the data-driven 3D design.

3.34 Appearance Fabrication

Philipp Urban (Fraunhofer IGD – Darmstadt, DE)

The Bright Future of Metameric Blacks.

3.35 Geometric Computing for Multi-Axis Additive Manufacturing

Charlie Wang (The Chinese University of Hong Kong, HK)

I will present our recent development of using multi-axis motion to conduct material accumulation along dynamically varied directions. Our development results in two approaches that mainly focus on how to avoid the additional supporting structures in a framework of volume-to-surface and then surface-to-curve decomposition. I will discuss a few future extensions of this framework so that to strengthen the function of 3D printed parts.

3.36 Appearance Fabrication: Challenges of Production Deployment

Tim Weyrich (University College London, GB)

Appearance fabrication aims at creating custom reflectance properties on real-world surfaces. As the inverse of appearance acquisition, it starts from a digital description of spatio-angular reflectance properties and seeks to alter physical surface to match that description. My talk provides a brief overview over the state of the art and then discusses a variety of key challenges when carrying academic proofs of concept into production environments, including the combination of multiple working principles for appearance fabrication, the challenge of countering visual artefacts of fabrication methods, the needs of mass production, and last not least of finding appearance specifications that have value in the applied context.

3.37 Multi- Material/Modality/Scale/Axis: Realizing Multi-Functional Products with Next-Generation AM Processes

Christopher Bryant Williams (VPI – Blackburg, US)

The maturation of Additive Manufacturing processes has provided access to unparalleled design freedom in product realization. For perhaps the first time, manufacturing capability outpaced that of the available design processes. While the recent acceleration in research of design automation tools and methodologies has closed this perceived gap, emerging AM processes capable of working at multiple length scales using multiple AM modalities along multiple axes to fabricate with multiple materials are expanding the gap between design and manufacturing yet again. The goal of this talk is to present these emerging AM capabilities in order to reflect on the corresponding needs of the next-generation design and computation tools.

3.38 Multi-Species Robot Ecologies for Space Making

Maria Yablonina (Universität Stuttgart, DE)

Over the past few decades, digital fabrication processes have been gaining momentum in the field of architecture and design. While the construction industry is racing to increase the efficiency of existing processes through automation of work in a conventional construction environment; the field of architectural research is implementing robotic technology towards discovering new materials, fabrication methods and ultimately a new design space. An industrial robot arm has become a somewhat iconic symbol of this undertaking. Research labs and institutions across the world push the boundaries of what is possible in architecture by augmenting robots with custom end-effectors and software, appropriating them for architectural tasks in all possible materials from brick and wood to 3D printed concrete and carbon fiber. However, could it be that today, when we are arriving at the point where processes no longer need to be designed specific to their human agent, the metaphor of the arm extension that the industrial robot suggests is not enough? This research is focusing on mobile robotic fabrication strategies specific to filament materials. Deploying smaller robots for manipulation of lightweight thread-like materials allows building significantly larger structures. Multiple task-specific machines developed in this research are designed to carry, manipulate, anchor and pass filament materials in an on-site architectural environment of interior space. This paper presents the current state of the catalogue of robot species developed in this research as well as the experiments and demonstrators performed to evaluate them. Ultimately this research aims to create a larger toolbox of hardware and software tools and methods for custom single-task fabrication and construction robots.

4 Working Groups

4.1 Algorithmic Reproducibility

Thomas Auzinger (IST Austria – Klosterneuburg, AT)

Joint work of Workshop participants

There has been a discussion on how to best publish research results that depend heavily on algorithmic components; this is often the case in computational research. Academic participants strongly favor the release of open-source program code that implements a proposed method. Thus, a benchmark implementation is immediately available which covers all the details that are omitted from the method's description in the published article. However, such behavior needs to be incentivized by the community and needs to be part of recruitment requirements. Providing open-source implementation should be expected from both students and faculty when applying for positions in academia. Also, peer review would need to establish the submission of source code as a necessary criterion for reproducibility. Otherwise, the additional effort of supplying usable code disadvantages the person that does it in comparison with peers that only focus on publications. It was also emphasized that the existence of published source code should be mentioned when presenting the associated project.

In contrast, several companies prefer detailed description of the method in supplementals. This preference originates from legal issues: incorporating source code that is similar to published variants could create of vulnerability during IP-related litigation. For the same reason, some copyright- and trademark-focused companies do not open-source their code at all.

5 Open Problems

5.1 Fabrication Reproducibility

Thomas Auzinger (IST Austria – Klosterneuburg, AT)

Joint work of Workshop participants

An issue that was voiced by large number of participants is the reproducibility of fabrication result on different 3D printing devices. Even 3D printers of the *same* model can behave very differently at different sites. Several concerns and proposals were voiced:

Calibration models: It might be useful to develop a repository of 3D models that can serve as a 3D printer benchmark. This should be a collaborative effort of the community and should highlight various aspects of a 3D printers capabilities – both from geometric and material aspects. This would allow for a standardized way of cross-device and/or cross-location comparisons.

Metrology: Having these models fabricated on one's 3D printer, it is still necessary to reliably measure the result in order to judge the printer capabilities and quality. For this, both an open source hardware solution was advocated for and a centralized measurement service. Any of these two allows a quantitative analysis of the fabrication device and would also constitute a community consensus on the topic. However, it was acknowledges that open source hardware would require much more effort and it is unclear how many research groups would invest the time to build such a device. Sharing such measurements with the community will provide an overview of fabrication tolerances and device reliability. Moreover, it would pressure printer manufacturer to address fabrication biases of their devices. In any case, the simple collection of 3D models will not be useful and a full-feedback pipeline as it exists in 2D printing is strongly desired. This would permit the recalibration of a device based on a set of standardized models.

Manufacturers: However, several participants reported that 3D printer manufacturers are not overly cooperative in opening their APIs to allow fine-grained calibration methods. They often rely on business models that rely on lock-in and the necessity of service contracts. Thus, it is unclear if (and to what extent) such community efforts would influence their corporate strategy.

Legal issues: Several participants strongly favored a GPL-based license for such a community project to ensure that all users of this data are forced to contribute to it. However, enforceability is unclear and it might prevent companies as well as printer manufacturers from using it at all.

References: NIST is currently preparing a benchmark test for 3D printers but focus on the low-level material properties in a first step. The talk by Carolyn C. Seepersad presented an implementation of various parts of the aforementioned issues. On a public webpage, example prints on many machines are available for comparison; this highlights the device uncertainties across different printers. At the same time, various open-source 3D printers are packaged with calibration patterns. The soft robotics community can also serve as an example for such efforts, as it routinely shares fabrication recipes.

It was also mentioned that such a rich collection of data might be useful for machine learning efforts (e.g., for automatizes device calibration or design).

5.2 Geometry Representation Guidelines

Thomas Auzinger (IST Austria – Klosterneuburg, AT)

Joint work of Workshop participants

Several participants pointed out the missing consensus on what the best geometry representations for different tasks are. For various parts of the manufacturing pipeline, different representations (e.g., meshes or voxels) are used, and they exact trade-offs between different approaches are not always known. As examples from the workshop, the talks by Alec Jacobson and Lin Sebastian Kayser highlighted advantages and disadvantages of both representations.

Especially from industry, it would be highly appreciated if standardized benchmarks on algorithms could be provided to make a more informed decision. This is especially relevant for fully-fledged design and production pipelines, where many computational and manual tasks are usually chained together. In such a context, it cannot be expected that a certain geometry representation proves superior for every subtask. At the same time, conversions between representations – in order to adapt them to the various subtasks – often causes information loss. Thus, an overall recommendation is usually hard to identify and would require future research.

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