Report from Dagstuhl Seminar 14361

Computational Aspects of Fabrication

Edited by

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 14361 "Computational Aspects of Fabrication".

Seminar August 31 to September 5, 2014 – http://www.dagstuhl.de/14361

1998 ACM Subject Classification I.3.8 [Computer Graphics] Applications, J.2 [Computer Applications] Physical Sciences and Engineering

Keywords and phrases Fabrication, Manufacturing Process Characterization (Additive Machining), 3D printing, Layered Manufacturing, 3D Rasterization, Geometric Modeling, Shape Perception, Material Properties (Mechanical/Optical)

Digital Object Identifier 10.4230/DagRep.4.8.126

1 Executive Summary

Marc Alexa
Bernd Bickel
Sara McMains
Holly E. Rushmeier

As manufacturing goes digital, the current understanding of industrial production will change fundamentally[1]. The digital age in manufacturing is coupled with new output devices that allow rapid customization and rapid manufacturing, revolutionizing the way we design, develop, distribute, fabricate, and consume products. We need to find computational models that support this new way of production thinking and lead its technological understanding. This opens challenges for many areas of science research, such as material science, chemistry, and engineering, but also and perhaps foremost computer sciences. The currently available digital content creation pipelines, algorithms, and tools cannot fully explore new manufacturing capabilities. To meet these demands, we need a deep understanding of computer graphics fundamentals: Shape, appearance of shape and materials, and physically-based simulation and animation. When designing an object, there is an inherent interplay among all these fundamental aspects.

[1] Special report: manufacturing and innovation. *The Economist* 403(8781):46, 2012.

The purpose of this seminar is to bring together leading experts from academia and industry in the area of computer graphics, geometry processing, and digital fabrication. The goal is to address fundamental questions and issues related to computational aspects of fabrication and jump-start collaborations that will pioneer new approaches in this area.

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3 Overview of Talks

3.1 From Digital to Physical: My Biased View

Moritz Baecher (Disney Research – Zürich, CH)

Joint work of Bächer, Moritz; Whiting, Emily; Bickel, Bernd; Sorkine-Hornung, Olga; James, Doug L.; Pfister, Hanspeter; Otaduy, Miguel A.; Lee, Hyunho R.; Matusik, Wojciech; Gross, Markus;
Main reference M. Bächer, E. Whiting, B. Bickel, O. Sorkine-Hornung, "Spin-It: Optimizing Moment of Inertia for Spinnable Objects," ACM Trans. on Graphics, 33(4):96, 2014.
URL http://dx.doi.org/10.1145/2601097.2601157

Additive Manufacturing (AM) technologies have advanced enough to enable 3D printing at high resolution, in full-color, and with mixtures of soft and hard materials. As opposed to subtractive manufacturing (SM) such as milling or drilling, they can fabricate highly complex assemblies without the need for a manual assembly of individual components. Yet, one of the major issues holding back widespread use of AM is the lack of efficient algorithms for the automated fabrication of digital CG, the reproduction of physical, and the computational design of content. I will talk about one instance of each: (1) a method to reproduce elastic deformation properties of real world objects, (2) the automated fabrication of articulated characters from skinned meshes, and (3) the computational design of spinnable objects by optimizing their moment of inertia.

3.2 Blue Sky – Computational Tissue Fabrication

Bernd Bickel (Disney Research – Zürich, CH)

In my talk I will report on very recent developments in the area of tissue engineering and 3D printing of tissue. I will give an overview of grand challenges current research groups are focusing on, such as creating a functional kidney and the technical challenges along this way, both from a hardware/materials and software perspective. Finally, I will highlight several computational challenges in this area and give my biased view on how the Computer Graphics community could contribute towards a BioCAD system, an essential component for designing and fabricating functional organs.

3.3 Adobe Research: 3D Printing for the Masses

Nathan Carr (Adobe Inc. – San José, US)

Joint work of Tim Reiner, Nathan Carr, Radomír Měch, Ondrej Stava, Carsten Dachsbacher, Gavin Miller
Main reference T. Reiner, N. Carr, R. Měch, O. Stava, C. Dachsbacher, G. Miller, "Dual-Color Mixing for Fused Deposition Modeling Printers," Computer Graphics Forum, 33(2):479–486, 2014; pre-print available from author's webpage.
URL http://dx.doi.org/10.1111/cgf.12319
URL https://cg.ivd.kit.edu/publications/2014/DCM/DualColorMixing.pdf

3D Printing is starting to become available for the masses. In this talk I will cover Adobe's efforts in this space and detail the 3D printing capabilities inside of its flagship product Photoshop. The capabilities inside of Photoshop were built upon technology developed inside of Adobe Research. I will cover a number of these technologies including Dual-Color Mixing for fused depositing Modeling Printers which provides a cool way to get continuous tone prints from two headed FDM print devices such as the Makerbot Replicator 2x. I will conclude with frontiers and challenges that I see this industry facing and what might be done to address some of these problems.

3.4 Design of Functional Models

Duygu Ceylan (EPFL – Lausanne, CH)

Joint work of Ceylan, Duygu; Li, Wilmot; Mitra, Niloy J.; Agrawala, Maneesh; Pauly, Mark
Main reference D. Ceylan, W. Li, N. J. Mitra, M. Agrawala, M. Pauly, "Designing and Fabricating Mechanical Automata from Mocap Sequences," ACM Trans. on Graphics, 32(6):186, 2013.
URL http://dx.doi.org/10.1145/2508363.2508400

Mechanical assemblies are collections of interconnected parts that move together to achieve specific functional goals. Such assemblies arise in various forms in our daily lives such as convertible furniture, kitchen supplies, mechanical toys etc. Enabling casual users to design such functional models requires to explore effective and intuitive ways of specifying the desired functionality. In this presentation, I will talk about our journey in experimenting with different interaction metaphors for specifying the desired functionality. This journey has led us to the development of an automatic system that can generate mechanical automata capable of realizing input motion sequences such as dancing or walking.

3.5 Research and Thoughts on 3D Printing

Yong Chen (University of Southern California, US)

The advent of 3D printing (additive manufacturing) and its use in rapid prototyping has drastically changed the design and manufacturing practice by enabling companies to prototype products faster and cheaper. With the price of 3D printers dramatically dropping in recent years, their accessibility is on the increase. However, significant challenges remain to be addressed in order for 3D printing to be used in direct digital manufacturing. My talk will introduce some of our research results on 3D printing processes including: (1) a complex internal structure design system for additive manufacturing; (2) a smooth surface fabrication process that can significantly improve the surface finish of curved surfaces; (3) a non-layer based 3D printing process named CNC accumulation for better part properties and building around inserts; (4) a deformation control strategy for 3D printing processes based on closed loop control and deformation simulation; (5) a support generation system for one of 3D printing processes (SLA); and (6) a digital material design method for multi- material 3D printing processes. I will also share some of my thoughts on some challenges and opportunities for computer graphics researchers.

3.6 Fabricating in constrained settings (with a human help)

Paolo Cignoni (CNR – Pisa, IT)

In the talk I will discuss three main topics: fabricating illustrative shapes with planar slices (Mesh Joinery), decomposing objects into interlocking pieces that can be manufactured by CNC and the use of anisotropic Voronoi diagrams to design a class of architectural structures called grid shells. Beside the details of these topics I will try to highlight "human in the end" issues that arise in digital fabrication techniques discussing how computational methods can improve the assembly problem.

3.7 From animated characters to legged robots

Stelian Coros (Carnegie Mellon University – Pittsburgh, US)

Computer graphics techniques allow artists to realize their imaginative visions, leading to immersive virtual worlds that capture the imagination of audiences world-wide. And now, thanks to advancements in rapid manufacturing devices, tangible links between these vivid virtual worlds and our own can be created. In order to unleash the full potential of this technology, however, a key challenge lies in determining the fundamental principles and design paradigms that allow digital content to be processed into forms that are suitable for fabrication. A particularly challenging task is that of creating physical representations of animated virtual characters in the form of complex robotic systems. In this talk, I will present evidence that control algorithms developed for physics-based character animation can also be applied to legged robots, allowing them to move with skill and purpose.

3.8 Design and Fabrication Using Wire Meshes

Bailin Deng (EPFL – Lausanne, CH)

Joint work of Akash, Garg; Sageman-Furnas, Andrew O.; Deng, Bailin; Yue, Yonghao; Grinspun, Eitan; Pauly, Mark; Wardetzky, Max
Main reference A. Garg, A. O. Sageman-Furnas, B. Deng, Y. Yue, E. Grinspun, M. Pauly, M. Wardetzky, "Wire mesh design," ACM Trans. on Graphics, 33(4):66, 2014.
URL http://dx.doi.org/10.1145/2601097.2601106

Wire meshes consist of interwoven metal wires arranged in a regular grid. Despite their widespread use in art, architecture, and engineering, it is challenging to design and fabricate freeform shapes using wire mesh material. One major difficulty is the global nature of wire mesh shapes: small local changes might have drastic global effects. In this talk, I will show how wire meshes can be modeled as discrete Chebyshev nets, which helps us to gain insights into their shape space and develop a computational design system for wire meshes. Moreover, I will present a method to physically realize freeform wire mesh shapes with the help of digital fabrication. Finally, I will discuss some open problems in this domain.

3.9 Perceptually-driven fabrication

Piotr Didyk (MIT – Cambridge, US)

In recent years there has been a tremendous development of new manufacturing technologies such as 3D printing. Despite the high quality of produced objects and the possibility of using multiple materials, reproducing 3D hardcopies of real objects is still a challenging task. Also the current level of understanding with regards to how these objects influence user experience is insufficient to fully utilize this kind of technology. In this talk, I will discuss importance of better understanding and modeling of human visual and haptic perception. I will present a few examples of how such knowledge combined with carefully designed computational techniques may lead to improved quality of manufactured objects.

3.10 Computational Fabrication Education at MIT

Piotr Didyk (MIT – Cambridge, US)

Joint work of Matusik, Wojciech; Levin, David; Didyk, Piotr

Hardly a 21st century day goes by without a reference to 3D printing and the revolution it is projected to cause in engineering and manufacturing. This enthusiasm is shared among hobbyists and within a vibrant maker community. During the last two years professor Wojciech Matusik and Dr. David Levin taught a novel course on computational fabrication at the Electrical Engineering and Computer Science Department at MIT. This talk provides an overview of the course material, programming assignments, and labs. Formally designated computational fabrication, 6.S079 provides a broad overview of both hardware and software for additive manufacturing. In particular, students are introduced to methods for parametric modeling of solid objects that take into account fabrication constraints. In the lab, they master computing models of physical objects using real-time 3D scanning. They also study and implement advanced physically- based simulation methods. The students explore the kinematics of mechanisms, such as four-bar-linkages, and finite element methods in the context of deformable solids. These techniques are fundamental in the engineering community and are crucial for designing highly predictive tools for 3D print preview. Using these tools, many variations of a virtual solid object can be interactively analyzed without committing to fabrication. The course also covers optimization methods that are applied to automate the design process. After learning this basic toolset, students analyze many instances of recent computational fabrication systems that seamlessly blend interactive design, simulation, and optimization, for example, the interactive designing of printable automata. In the second part of the semester, students work in groups on large open-ended projects. The primary goal of the class is to give students both a practical and a theoretical knowledge of every stage in the computational fabrication pipeline – raising awareness about this rapidly expanding field.

3.11 On the Challenges of Manufacturing

Gershon Elber (Technion – Haifa, IL)

In this two-parts talk I will first consider the major deficiencies I see in modern geometric modeling tools, and give some insights into what the next generation geometric modeling abilities should be, as I see them.

Then, I will exemplify the difficulties of manufacturing via a sequence of artifacts that went through the design-to-manufacturing process.

3.12 Fabricating Optics

Wolfgang Heidrich (KAUST – Thuwal, SA)

Modern fabrication methods show great promise for prototyping components for optical systems in computational imaging and display. In this talk I will report on some recent work in designing freeform lenses for goal-driven caustics, and then describe several experiments for fabricating these shapes on polyjet 3D printers as well as inexpensive 3-axis mills. I will report on issues with finishing the resulting shapes to optical grade. Finally I will descibe some initial approaches for fabricating custom diffractive optical elements in KAUST's Nanofabrication Lab.

3.13 Zometool Shape Approximation

Leif Kobbelt (RWTH Aachen, DE)

Joint work of Zimmer, Henrik; Florent, Lafarge; Alliez, Pierre; Kobbelt, Leif
Main reference H. Zimmer, F. Lafarge, P. Alliez, L. Kobbelt, "Zometool Shape Approximation," Graphical Models, 76(5):390–401, 2014.
URL http://dx.doi.org/10.1016/j.gmod.2014.03.009

We present an algorithm that approximates 2-manifold surfaces with Zometool models while preserving their topology. Zometool is a popular hands-on mathematical modeling system used in teaching, research and for recreational model assemblies at home. This construction system relies on a single node type with a small, fixed set of directions and only 9 different edge types in its basic form. While being naturally well suited for modeling symmetries, various polytopes or visualizing molecular structures, the inherent discreteness of the system poses difficult constraints on any algorithmic approach to support the modeling of freeform shapes. We contribute a set of local, topology preserving Zome mesh modification operators enabling the efficient exploration of the space of 2-manifold Zome models around a given input shape. Starting from a rough initial approximation, the operators are iteratively selected within a stochastic framework guided by an energy functional measuring the quality of the approximation. We demonstrate our approach on a number of designs and also describe parameters which are used to explore different complexities and enable coarse approximations.

3.14 Natural User Interfaces for Digital Fabrication

Manfred Lau (Lancaster University, GB)

Joint work of Lau, Manfred; Saul, Greg; Mitani, Jun; Igarashi, Takeo; Weichel, Christian; Kim, David; Villar, Nicolas; Gellersen, Hans

I discuss three natural user interface tools for digital fabrication. The motivation for such interfaces is that easy-to-use tools for 3D modeling and fabrication is still lacking, despite years of research in developing modeling tools for novice users. The recent trend of rapid prototyping technologies such as 3D printers will lead to an increased demand for these interfaces for fabrication purposes. The first system (SketchChair) is a sketch-based interface where the end-user can participate in the whole process of designing, modeling, and fabricating chairs with a laser cutter. The second system (Situated Modeling) has a tangible interface for modeling 3D shapes in an augmented reality environment. The user can immersively create and edit 3D shapes with a small number of physical primitive shapes, and with the guidance of the real-world environment and existing objects. The third system (MixFab) is a hand gesture based interface that takes advantage of a mixed reality environment to model small everyday objects that can be 3D printed. I end by speculating potential future interfaces for fabrication with the concept of Embodied Modeling and Fabrication.

3.15 Slicing for additive manufacturing: A computer graphics point of view

Sylvain Lefebvre (LORIA & INRIA – Nancy, FR)

Joint work of Lefebvre, Sylvain; Hergel, Jean; Dumas, Jérémie
URL http://www.aracknea-core.com/sylefeb/research/

In this talk I will introduce our work on slicing for additive manufacturing. We build upon recent GPU rendering techniques to directly slice objects specified using a Constructive Solid Geometry language. Our technique directly produces the code to drive the printer, without having to produce an intermediate mesh.

This led us to several software improvements to make printing on low cost printing more reliably, in particular for multi-material prints and for the generation of stable support structures.

References

1. Bridging the Gap: Automated Steady Scaffoldings for 3D Printing, J. Dumas, J. Hergel, S. Lefebvre, ACM SIGGRAPH, 2014
2. Clean color: Improving multi-filament 3D prints, J. Hergel, S. Lefebvre, EUROGRAPHICS 2014
3. IceSL: A GPU Accelerated modeler and slicer, S. Lefebvre, 18th European Forum on Additive Manufacturing, 2013

3.16 Rendering, Animating, and Fabricating Volumetric Materials

Steve Marschner (Cornell University – Ithaca, US)

Joint work of Bala, Kavita; Bickel, Bernd; Jakob, Wenzel; James, Doug; Jarosz, Wojciech; Kaldor, Jon; Matusik, Wojciech; Papas, Marios; Yuksel, Cem; Zhao, Shuang

For rendering and animation of textiles, detailed models of the material structure are useful in producing highly realistic results.

For coarse knit fabrics, we have simulated both the structure and deformation of intricate lace patterns and complex garments in terms of the geometry and motion of individual yarns, producing texture and motion that closely resemble the real materials. For woven fabrics, we have used micro CT scans to model the geometric arrangement of fibers at the microscopic scale, leading to highly realistic images that exhibit the distinctive texture and sheen of these materials. In both cases, the needs of realism have driven us to work directly in terms of the descriptions used to fabricate the materials: patterns for hand knitting and the binary images used by industrial Jacquard looms.

This is a general trend in realistic rendering and animation, and translucent materials are another case where the descriptions used for rendering are quite direct specifications for the material itself. We have developed a system that calibrates a particular pigmentation system, then can measure a translucent material and uses rendering techniques inversely to compute a recipe for making a material that matches it.

3.17 Geometric Analysis for Manufacturing: Conventional vs. Additive Manufacturing

Sara McMains (University of California – Berkeley, US)

Joint work of McMains, Sara; Yasui, Yukuse; Li, Wei

I present computational geometry algorithms that we developed to support manufacturing process planning for waterjet cleaning (used to remove manufacturing byproducts in conventional manufacturing processes). Parallels with process planning for additive manufacturing are discussed.

3.18 Creating Works-Like Prototypes Of Mechanical Objects

Niloy Mitra (University College London, GB)

Joint work of Koo, Bongjin; Li, Wilmot; Yao, JiaXia; Agrawala, Maneesh; Mitra, Niloy
Main reference B. Koo, W. Li, J. Yao, M. Agrawala, N. J. Mitra, "Creating Works-Like Prototypes of Mechanical Objects," ACM Trans. on Graphics, 33(6):217, 2014; pre-print available from author's webpage.
URL http://dx.doi.org/10.1145/2661229.2661289
URL http://geometry.cs.ucl.ac.uk/projects/2014/works-like/

Designers often create physical works-like prototypes early in the product development cycle to explore possible mechanical architectures for a design. Yet, creating functional prototypes requires time and expertise, which discourages rapid design iterations. Designers must carefully specify part and joint parameters to ensure that the parts move and fit and together in the intended manner. We present an interactive system that streamlines the process by allowing users to annotate rough 3D models with high-level functional relationships (e. g., part A fits inside part B). Based on these relationships, our system optimizes the model geometry to produce a working design. We demonstrate the versatility of our system by using it to design a variety of works-like prototypes.

References

1 Bongjin Koo, Wilmot Li, JiaXian Yao, Maneesh Agrawala, Niloy J. Mitra. *Creating Works-Like Prototypes of Mechanical Objects.* ACM Transactions on Graphics (Special issue of SIGGRAPH Asia 2014), 2014.

3.19 Interacting with Personal Fabrication Devices – Current challenges from an HCI perspective.

Stefanie Müller (Hasso-Plattner-Institut – Potsdam, DE)

Joint work of Müller, Stefanie; Baudisch, Patrick; Guimbretière, François
Main reference S. Müller, S. Im, S. Gurevich, A. Teibrich, L. Pfisterer, F. Guimbretiere, P. Baudisch, "WirePrint: Fast 3D Printed Previews," in Proc. of the 27th ACM User Interface Software and Technology Symposium (UIST'14), pp. 273–280, ACM, 2014; pre-print available from author's webpage.
URL http://dx.doi.org/10.1145/2642918.2647359
URL https://www.hpi.uni-potsdam.de/baudisch/home.html

In this talk, I discuss three challenges when interacting with personal fabrication devices: (1) Personal fabrication machines, such as 3D printers, are so slow that many objects require printing overnight. This limits designers to a single design iteration per day even though the actual design work between each iteration was only a couple of minutes. With our projects, faBrickation and WirePrint, we address this problem by allowing designers to fabricate intermediate versions of a prototype as fast, low-fidelity previews, and to only create the final version as a full 3D print. (2) Currently users use a digital editor to design physical objects. There are good reasons for doing this since the digital world allows for precise interaction and editing steps can be easily undone. However, having the input and output space separated is not intuitive for novice users. With our projects constructable and LaserOrigami, we show how to merge input and output space by letting users work directly on the physical workpiece and by creating physical output after every step. (3) Personal fabrication tools allow us to create more and more things. With our project Scotty, we question that more is always better as having more affects how we value a single object. With Scotty, we show how to relocate physical objects across distances by ensuring that there is never more than one copy at a time, i. e. the object disappears on the sender side and reappears on the receiver side, thereby preserving its value.

3.20 Computational Caustics

Mark Pauly (EPFL – Lausanne, CH)

Joint work of Pauly, Mark; Yuliy Schwartzburg, Romain Testuz, Andrea Tagliasacchi
Main reference Y. Schwartzburg, R. Testuz, A. Tagliasacchi, M. Pauly, "High-contrast Computational Caustic Design," ACM Trans. on Graphics, 33(4):74, 2014.
URL http://dx.doi.org/10.1145/2601097.2601200
URL http://lgg.epfl.ch/publications/2014/HighContrastCaustics.pdf

We present a new algorithm for computational caustic design. Our algorithm solves for the shape of a transparent object such that the re- fracted light paints a desired caustic image on a receiver screen. We introduce an optimal transport formulation to establish a correspon- dence between the input geometry and the unknown target shape. A subsequent 3D optimization based on an adaptive discretization scheme then finds the target surface from the correspondence map. Our approach supports piecewise smooth surfaces and non-bijective mappings, which eliminates a number of shortcomings of previous methods. This leads to a significantly richer space of caustic images, including smooth transitions, singularities of infinite light density, and completely black areas. We demonstrate the effectiveness of our approach with several simulated and fabricated examples.

3.21 Interactive modeling with developable NURBS surfaces

Helmut Pottmann (KAUST – Thuwal, SA)

Joint work of Tang, Chengcheng; Pottmann, Helmut

Developable surfaces play an important role in various manufacturing technologies, since they model the natural behavior of materials which do not stretch. Although there is a rich literature on modeling these surfaces, the interactive design of developable NURBS surfaces is still a challenge. Employing a combination of the standard and the dual representation, we propose an efficient numerical constraint solver which overcomes the limitations of previous work. While the user manipulates the B-spline control structure, the surfaces get automatically corrected in real time towards developable NURBS surfaces with high numerical accuracy. We illustrate our framework by various types of developable strip models and present initial results on models with curved folds. This is ongoing unpublished research.

3.22 Computational / Physical Light Routing: 3D Printed Fiber Optics

Szymon Rusinkiewicz (Princeton University, US)

Joint work of Pereira, Thiago; Rusinkiewicz, Szymon; Matusik, Wojciech
Main reference T. Pereira, S. Rusinkiewicz, W. Matusik, "Computational Light Routing: 3D Printed Fiber Optics for Sensing and Display," ACM Trans. on Graphics, 33(3):24, 2014.
URL http://dx.doi.org/10.1145/2602140

Despite recent interest in digital fabrication, there are still few algorithms that provide control over how light propagates inside a solid object. Existing methods either work only on the surface or restrict themselves to light diffusion in volumes. We use multi-material 3D printing to fabricate objects with embedded optical fibers, exploiting total internal reflection to guide light inside an object. We introduce automatic fiber design algorithms together with new manufacturing techniques to route light between two arbitrary surfaces. Our implicit algorithm optimizes light transmission by minimizing fiber curvature and maximizing fiber separation while respecting constraints such as fiber arrival angle. We also discuss the influence of different printable materials and fiber geometry on light propagation in the volume and the light angular distribution when exiting the fiber. Our methods enable new applications such as surface displays of arbitrary shape, touch-based painting of surfaces and sensing a hemispherical light distribution in a single shot.

3.23 3D Printing Tools in Meshmixer (Support Structures, Strength Analysis, etc)

Ryan Schmidt (AUTODESK Research – Toronto, CA)

3D printing is becoming increasingly practical as a technique for one-off fabrication of customized objects and small-batch manufacturing. In many applications, the 3D printer provides a means to solve problems that would be prohibitively expensive to address in any other way. I will present three example use cases in aerospace, manufacturing, and prosthetics that illustrate how both professional and consumer-level 3D printers are being used today. However, the premise of automatically fabricating an arbitrary 3D design remains more hype than reality. Based on extensive observation of users of Autodesk meshmixer, discussion with domain experts, and personal experience, I have noted many issues which could be addressed with the mathematical tools of computer graphics and geometry processing. I will describe a set of current challenges in the 3D printing pipeline that hinder user creativity and prevent many seemingly-straightforward applications.

3.24 User-Guided Inverse 3D Modeling

Carlo H. Sequin (University of California – Berkeley, US)

Joint work of Andrews, James; Sequin, Carlo H.
Main reference J. Andrews, "User-Guided Inverse 3D Modeling," Ph. D. Thesis, U. C. Berkeley, May 2013.
URL http://www.eecs.berkeley.edu/Pubs/TechRpts/2013/EECS-2013-103.pdf

Few designs start from scratch in a vacuum. Often there is a previous artifact that provides inspiration or may even be close enough so that some high-level redesign might be the most effective approach. Unfortunately there may be no CAD files available or they may be at such a low level (100'000 triangles) that it is not a good starting point for a major redesign. "User-Guided Inverse 3D Modeling" is an approach to re-create a well-structured, high-level, parameterized, procedural description of some geometry very close to the inspirational artifact. Its hierarchical structure and the degree of its parameterization are imposed with some high-level instructions by the designer, so that the resulting description is most appropriate to make the intended design changes.

3.25 Use the winding number to determine "inside" and "outside" for each level in layered manufacturing

Carlo H. Sequin (University of California – Berkeley, US)

Models of trusses consisting of many joining or intersecting beams, often with non-trivial cross sections, may result in a solid model that does not have a proper, oriented, 2-manifold boundary representation. Cleaning up such a 3D model is laborious and difficult, even when the individual components (beams) themselves have perfectly good B-Reps. Sending such "unclean" models to a layered manufacturing machine will often produce unexpected result – or will simply be refused by the machine's software. This problem could easily be remedied by slicing all components individually, paying careful attention to the orientation of the surface normals, and then forming the Boolean union of all the extracted slicing contours on each level while summing up their respective winding numbers.

3.26 Modular Models of Mathematical Knots

Carlo H. Sequin (University of California – Berkeley, US)

The LEGO-Knot system is a collection of tubular parts with a 1" square cross-section that are compatible with the LEGO DUPLO blocks. It was originally inspired by the modular "Borsalino" sculpture by Henk van Putten presented in the art exhibition of the Bridges 2013 conference in Enschede, Netherlands. Currently this set of prototype parts is rich enough so that a wide variety of free-form tubular sculptures can be assembled, and simple mathematical knots like the Trefoil Knot and the Figure-8 Knot can be modeled in a graceful manner with the sweep curve closing smoothly onto itself. Recently I have given myself the challenge to design a single tubular element that would be versatile enough for modeling many of the simple mathematical knots in a similar graceful manner. The resulting tubular module is based on a cross-section in the form of a regular 16-gon and bends through an angle of 30 degrees. Now the remaining challenge is to develop an effective search algorithm that can find elegant solutions for most of the simple knots. Through manual search stretching over a few hours, good solutions have been found for the Trefoil Knot, the Figuee-8 Knot, and the Knots 5-1 and 7-4, as well as for the Borromean Link. The challenge remains to find a good automated search algorithm. This problem was presented at this seminar, because it has similarities with the design problem discussed by Leif Kobelt: How to best approximate an arbitrary 2-manifold such as the surface of the Stanford Bunny with a mesh made solely from Zome Tool parts.

3.27 Computational Design-to-Fabrication

Kristina Shea (ETH Zürich, CH)

In this talk I will introduce Computational Design-to-Fabrication from an engineering and product design viewpoint, give an overview of our research on design automation and optimization of structural and mechanical systems and a glimpse into new research making the link to automated fabrication via additive manufacturing, mainly multi-material.

3.28 Flat Fabrication

Karan Singh (University of Toronto, CA)

Joint work of Singh, Karan; McCrae, James
Main reference J. McCrae, N. Umetani, K. Singh, "FlatFitFab: Interactive Modeling with Planar Sections," in Proc. of the 27th Annual ACM Symp. on User Interface Software and Technology (UIST'14), pp. 13–22, ACM, 2014.
URL http://dx.doi.org/10.1145/2642918.2647388
URL http://flatfab.com/

Assembled planar section structures are common in art and engineering. This talk presents the state of the art on the computational abstraction of 3D shape using planar sections. It also describes a comprehensive drawing interface to author planar section structures from scratch, based on principles of inter-plane orthogonality, procedural regularity and fronto-parallel drawing. Finally, a number of open problems and issues specific to flat fabrication are described, along with speculated solutions and directions for future work.

3.29 Computational Design and Fabrication of Deformable Objects

Melina Skouras (Disney Research – Zürich, CH)

Joint work of Skouras, Melina; Thomaszewski, Bernhard; Bickel, Bernd; Coros, Stelian; Kaufmann, Peter; Bradley, Derek; Beeler, Thabo; Jackson, Phil; Marschner, Steve; Matusik, Wojciech; Gross, Markus

Deformable objects have a plethora of applications: they can be used for entertainment, advertisement, engineering or even medical purposes. However designing custom deformable objects remains a difficult task. The designer must foresee and invert effects of external forces on the behavior of the figure in order to take the proper design decisions. In this talk, I will present novel approaches based on physics-based simulation and inverse optimization techniques which alleviate these difficulties and propose a complete framework to design custom deformable objects by automating some of the most tedious aspects of the design process. This framework is tailored to the design of various objects such as rubber balloons, skin for animatronics figures and custom actuated characters, for which optimization of diverse variables including rest shape, materials and actuation system is alternately considered. Validation of our method is performed by fabricating representative sets of physical prototypes designed with our method and compared to the results predicted by simulation.

References

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3.30 Designing Mechanical Characters

Bernhard Thomaszewski (Disney Research – Zürich, CH)

The design of virtual characters has been in the focus of graphics research since its very beginnings. With the advent of 3D printers we now have the machinery to create tangible, physical counterparts of digital characters that can be used as input devices for video games, mechanical toys, or even animatronics. But besides progress in manufacturing technology, we need progress in software tools to facilitate the translation from virtual to real characters. This talk addresses a number of challenges that arise when designing mechanical characters, in particular the question of how to design mechanisms that are able to reproduce a desired motion.

3.31 Interactive Design of Functional Shapes

Nobuyuki Umetani (Disney Research – Zürich, CH)

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Physical simulation allows validation of geometric designs without tedious physical prototyping. However, since geometric modeling and physical simulation are typically separated, simulations are mainly used for rejecting bad design, and, unfortunately, not for assisting creative exploration towards better designs. In this talk, I introduce several interactive approaches to integrate physical simulation into geometric modeling to actively support creative design process. More specifically, I demonstrate the importance of (i) presenting the simulation results in real-time during user's interactive shape editing so that the user immediately sees the validity of current design, and to (ii) providing a guide to the user so that he or she can efficiently explore the valid deign space. I present novel algorithms to achieve these requirements.

3.32 Crafting Light by Hacking Pixels

Gordon Wetzstein (Stanford University, US)

Compressive image acquisition and display is an emerging architecture for consumer electronics that explores the co-design of optics, electronics, applied mathematics, and real-time computing. Together, these hardware/software systems exploit compressibility of the recorded or presented data to facilitate new device form factors and relax requirements on electronics and optics. For instance, light field or glasses-free 3D displays usually show different perspectives of the same 3D scene to a range of different viewpoints. All these images are very similar and therefore highly compressible. By combining multilayer hardware architectures and directional backlighting with real-time implementations of light field tensor factorization, limitations of existing displays, for instance in resolution, contrast, depth of field, and field of view, can be overcome. A similar design paradigm also applies to light field and multi-spectral image acquisition, super-resolution and high dynamic range display, glasses-free 3D projection, computational lithography, microscopy, and many other applications. In this talk, we review the fundamentals of compressive camera and display systems and discuss their impact on future consumer electronics, remote sensing, scientific imaging, and human-computer interaction.

3.33 Crafting Light by Hacking Pixels

Gordon Wetzstein (Stanford University, US)

Joint work of Wetzstein, Gordon; Raskar, Ramesh; Lanman, Douglas; Hirsch, Matthew
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With the invention of integral imaging and parallax barriers in the beginning of the 20th century, glasses-free 3D displays have become feasible. Only today – more than a century later – glasses-free 3D displays are finally emerging in the consumer market. The technologies being employed in current-generation devices, however, are fundamentally the same as what was invented 100 years ago. With rapid advances in optical and digital fabrication, digital processing power, and computational models for human perception, a new generation of display technology is emerging: computational displays exploring the co-design of optical elements and computational processing while taking particular characteristics of the human visual system into account. This technology does not only encompass 3D displays, but also next-generation projection systems, high dynamic range displays, perceptually-driven devices, and computational probes.

This talk serves as an introduction to the emerging field of computational display fabrication. We will discuss a wide variety of different applications and hardware setups of computational displays as well as their fabrication, including high dynamic range displays, advanced projection systems as well as glasses-free 3D display. We will only briefly review conventional technology and focus on practical and intuitive demonstrations of how an interdisciplinary approach to display design and fabrication encompassing optics, perception, computation, and mathematical analysis can overcome the limitations for a variety of applications.

3.34 Appearance Fabrication

Tim Weyrich (University College London, GB)

Joint work of Weyrich, Tim; Hullin, Matthias B.; Ihrke, Ivo; Fuchs, Martin; Papas, Marios; Jarosz, Wojciech; Jakob, Wenzel; Rusinkiewicz, Szymon; Matusik, Wojciech

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 an overview over working principles employed by prior art, and raises a number of questions on future directions of appearance fabrication.

3.35 Structurally-Informed Geometry

Emily Whiting (Dartmouth College – Hanover, US)

Joint work of Whiting, Emily; Prevost, Romain; Lefebvre, Sylvain; Sorkine-Hornung, Olga; Baecher, Mortiz; Bickel, Bernd; Deuss, Mario; Panozzo, Daniele; Liu, Yang; Block, Philippe; Pauly, Mark

In computer graphics, many of the 3D objects we are interested in modeling are physically-inspired or are designed with the intent of being built or manufactured. Yet many of the tools developed for geometric modeling are unaware of structural considerations, largely based on geometric surface characteristics alone. The motivation for my work is to use structural soundness and stability properties to enhance the traditional modeling pipeline. I will discuss recent work investigating structurally-informed design of 3D printed objects. Time permitting, I may also review topics in the design of masonry structures.

3.36 Small-scale Structure and Material Properties

Denis Zorin (New York University, US)

Joint work of Zhou, James; Panetta, Julian; Zorin, Denis

Complex structures are widely used to achieve optimal mechanical performance (e. g., minimize weight for given strength). In traditional manufacturing, the cost is proportional to complexity; additive manufacturing makes complexity almost independent from cost, making much more complex with novel properties possible. In particular, one can create small-scale structures, approximating homogeneous material properities. Optimizing such structures directly is difficult. I describe a multistage process process for optimizing small-scale structures, usually referred to as "optimization by homogenization": a map from material properties to structure parameters is constructed, then continuous material properties are optimized and mapped to a tiled structure using this map. Experiments show that a number of structure optimization problems can be solved in this way.

4 Open Problems and Panel Discussion

Based on the ideas from the individual presentations, there were group discussions on four topics. First there was a discussion of particular problems that have been posed in fabrication, and the applications that motivate these problems. This list of problem definitions was a major outcome of the meeting. The group discussed particular issues that need to be resolved for these specific problems. Second, on a more general level, the role of computer graphics research in fabrication was discussed, in light of the activities in other disciplines. Third, the fabrication processes that the computer graphics community should consider working on was discussed. Finally, the need for systems to assist in the design of custom fabricated objects emerged as a major theme in the meeting. The group tried to define the different types of user populations, and their needs for design systems.

4.1 Problems/Applications

Many overlapping ideas were identified from the various presentations. These were combined to identify specific computations problems and the applications that motivate them.

Problem: A general problem is the production of a particular shape from fixed set of physical primitives. Problems related to this include how to produce a set of primitives that can express a wide variety of shape and how to produce instructions for assembling shape from primitives.

Applications: Toys (e. g. Lego-type systems), sets of physical objects for illustrating concepts.

Discussion: This is actually a large group of problems, and designing with orthogonal planar pieces is also in this set, as well as design with specific geometric constraints. As well as the toy and illustrative applications, systems based on fixed primitives are useful in architectural design exploration.

Problem: Design structures to achieve spatially varying physical properties (Young's modulus, Poisson ratio). One approach to this is to emulate complex designs previously found only in nature (e. g. bird bones). Solutions need to include not just one structure, but the description of the rest geometry and functionality, and these must stay within limits of manufacture. Achieving particular properties can be achieved with structure and by using mixes of material.

Applications: Helmets, custom footwear.

Discussion: To study material variation, we need collaborators in materials science and mechanical structures. Computer graphics can contribute models of humans that these objects need to fit. Computer graphics can also contribute simplified simulations of very complex structures. Manipulating and representing very complex geometries is an area of computer graphics. We need to create tools to design combinations for hard and soft materials – e. g. cases for phones etc.

Problem: Design assemblies with specific motions. The motions may be controlled in different ways – for example with a single input crank or by being propelled by something. There are different ways that motions can be described. Existing libraries of mechanisms can be used in the solutions. Beyond just rigid linkages, the motion of deformable surfaces can also be designed.

Applications: Toys, animatronics, design of artificial limbs.

Discussion: We need to model deformations in many settings to understand the manufacturing process. We now have the opportunity to put complex mechanisms in ANY object – how can we exploit this to make new useful things?

Problem: Fabrication of new optical components. This can provide new dimensions in viewing (stereo/hi dynamic range, light field). Displays can be made in arbitrary shapes. Are deposition methods good enough, or are they just a proof of concept technology?

Applications: New displays, cameras.

Discussion: Optical systems need post-processing, i. e. polishing and assembly. These operations need to be included in the design of the fabrication process. The human is part of the fabrication process. We need to model the role the human can play to a greater extent. We need to design work flows between stages in the fabrication process. In this an other applications, we need a place to document methods and best practices.

Problem: UI's for: Design of objects by function and manufacture technique (furniture, orthogonal planes). Design of objects in context of real objects (augmented reality). Design of objects with performance analysis built into design system (musical instruments).

Applications: Universal.

Discussion: We need UI's for designing UI's. We need more exploration of data driven techniques in place of simulations in the interface. We need a common language to communicate designs to printers, to communicate with modules for doing clean-up of models. Is the answer STL? Or AMF (Hod Lipson's initiative)? In the UI, when we are designing to fit in the physical world, do we think of bringing the digital into the physical world, or the physical into the digital world?

Problem: Drawbacks of FDM – Design alternative additive manufacture systems. Redesign system for obtaining smooth surfaces. Many manufacturing processes are not supported computationally.

Applications: Optical systems where surface quality is critical.

Discussion: In the near future more patents will expire, and additional types of fabrication will become cheap. However, those techniques may have their own drawbacks as far as materials required (cost, stability). In general we need to document the limitations of machines. This is a moving target with the technology changing. How do we abstract to the correct level? What can we learn from the more mature field of 2D printing on how they have characterized machines?

Problem: Appearance Reproduction. Is FDM too limited? Simulation for other manufacturing processes? What will be the role of perception?

Applications: Prototype appearance, assist traditional manufacture.

Discussion: While appearance reproduction is limited, as long as machines are being used for prototyping and evaluation it is important to do the best job possible reproducing appearance and haptic/tactile properties.

4.2 Computational Fabrication and Computer Graphics

Computer graphics is still finding its place in computational fabrication research. To some extent we are solving new problems, but to some extent we are rediscovering problems other people have solved.

A good way to speed up productive work is through community software initiatives. An open source library that can support low-end fabrication devices would quickly benefit from the efforts of many people who are studying fabrication.

Currently G-code is the current common tool for software. Can we do better? Many people write their own slicers, but access to machine control is making this harder. Should we start a coordinated effort to develop open source software?

CNC machines became easier to control and more open, will the same happen for 3D printing? Standardizing on a poor scheme like G-code could be dangerous and limiting. Other examples of systems that opened up are GPUs, and Epson printers. What motivates companies to make software that controls more open? We need to find a way to demonstrate to them the financial benefit of openness.

We need to provide a place (perhaps a wiki or similar site) to capture documentation of methods and best practices. Useful software could evolve from these methods and practices.

4.3 Targeted Fabrication Processes

A lot of current fabrication work in computer graphics centers around FDM – fused deposition modeling. Other computer controlled machining processes, as well as hybrid FDM and computer controlled making processes could benefit from advanced computational methods.

In the 1980's, computer graphics was closely tied with the CADAM (computer aided design and manufacturing) communities. The current interest in computational fabrication is an opportunity to renew ties with that community. The computer graphics community should avoid focussing on a single manufacturing technology.

4.4 Design Systems

A major issue in computation for fabrication is the development of UI's (user interfaces). UI's need to be designed for different types of users, and for different phases of design.

In fabrication, there are at least three different groups of users – novices, "do it yourself" users with a high level of expertise, and professional designers.

For novices, a very restricted design space is useful. It may be that novices are really just customizing, not designing, objects.

No one stays a novice. Is it the generality of the design vs a very constrained space? We need "scalable" UI's that move from general concepts to specifics.

Design systems can simulate the fabrication process and the performance of the final object. In the user interface we need to take into account what the users wants – just an object sent to them, or an object in which they have participated in the production.

Professional designers move from general concepts to detail specification. Design exploration needs rapid generation of variations. Specification needs precision. We need bridges between systems to do this, to flow from concept to precision. Consider that another group that uses systems are decision makers. We need a seamless tool chain.

4.5 Open Questions and Future Research Directions

During the final session of the workshop we again discussed important open questions and potential future research directions. Ten areas were discussed, as listed below, building on the discussion during Ryan Schmidt's earlier presentation.

Open questions that in many cases participants have done research on in the past, but that didn't lead to much additional discussion during this session, included:

- Better surface quality
- Better support structures
- Light-weighting and hollowing
- Multi-objective orientation optimization

Open questions that inspired more discussion:

- Generation of G-code paths. Optimal paths for 3-D printing differ from optimal paths for machining, where toolpath generation has been widely studied. The patterns are very different for additive versus subtractive G-code. There are also aspects of fluids that are relevant; approximate models could be very useful. We need a good simulator for 3-D printing (perhaps along the lines of the Vericut software that is widely used for CNC). Right now some designers will have the software generate a G-code path from a preliminary design, examine the path to gain insight about whether the design will print well, and redesign based on what they can see visually in the toolpath, but an actual simulator would give even more useful feedback.
- Ensuring printability. One example where there has been some research but more can be done is in the area of selective thickening of geometry. One example where this is very useful is for architectural models, where when an architect scales down a model of a house uniformly in order to print it, the banisters all break because they become too thin for the target printer.
- Tolerance and clearance analysis. Here one of the important differences compared to conventional manufacturing is the need for anisotropy-aware algorithms.
- Nesting and packing. There is lots of literature in two dimensions, but less in 3-D. The commercial system Magics supports 3-D packing, but it is slow.
- Residual stress estimation and correction. There has been some work on estimation, but no one at the workshop was aware of much work on correction. Active positioning with feedback is not enough, because the warping often happens later, as subsequent layers cool/solidify. With cheap printers, people have seen awful warping. Perhaps printing a calibration part for testing, evaluating it with a computer vision system, and setting parameters based on current working conditions surmised from the behavior of the calibration test part is an approach that is worth studying.
- Planning support material removal. This could include planning escape holes, or a series of orientations for emptying the part interior. For example, injection molds need to be designed with cooling channels. Now that people are 3-D printing molds, the geometry of the channels is suddenly getting much more complex because 3-D printing doesn't have tooling accessibility issues. But now the un-sintered powder or dissolved support material needs to be removed. Accessibility for cleaning the part to remove this excess material after printing becomes the issue instead.

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