

3D PRINTING RESEARCH IN UBICOMP & BEYOND

CSE 590 Ubiquitous Computing | Lecture 10 | May 31

Jon Froehlich • Liang He (TA)

SCHEDULE TODAY: 6:30-9:20

06:30-07:00: Co-Motion Makerspace for 3D printing

07:00-07:20: Discussion of required Abowd reading led by Apurv

07:20-07:30: Discussion of optional Aylett reading led by Alex ([link](#))

07:30-08:30: Fabrication research in computer science

08:30-08:50: Course evaluations

08:50-09:20: Wrapping up

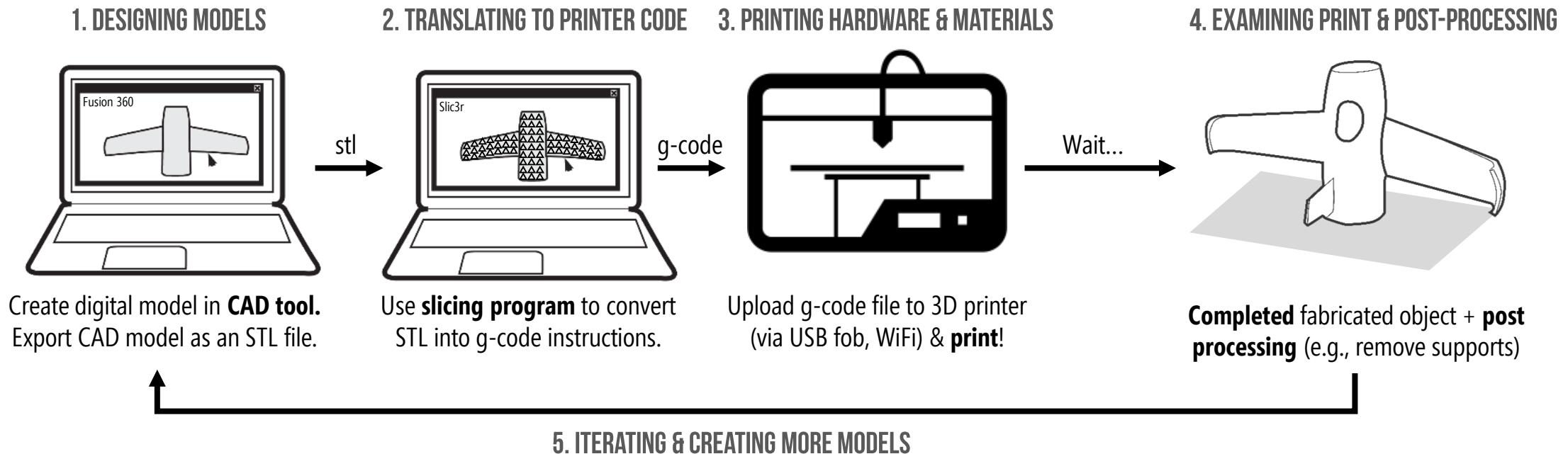
FINAL CLASSTIME THURS, JUNE 7 AT 6:30

We will meet next Thurs, June 7 at 6:30PM (regular time)

For those interested, we will have a show-and-tell of A4+A5

Please return your equipment (Android, Arduino, circuit kits)

3D-PRINTING MANUFACTURING PROCESS



Our focus is on **3D-printing research in CS**—particularly in Graphics, HCI, and UbiComp—rather than material science or mechanical engineering.

EXAMPLE KEY QUESTIONS

How can we **lower barriers** to fabricating objects?

How can we **expand** what can be constructed?

How can we improve the **robustness, speed, etc.** of FDM?

How can we fundamentally **transform the CAD** experience?

How can we **reduce waste** and improve sustainability?

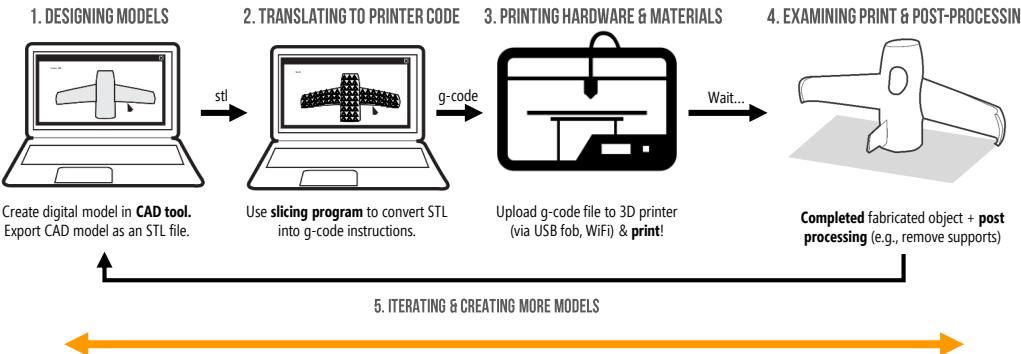
MAKING DEFORMABLE OBJECTS

MOST 3D-PRINTED OBJECTS ARE STATIC “TRINKETS”



MAKING DEFORMABLE OBJECTS

HOW TO CREATE DEFORMABLE 3D-PRINTED OBJECTS



This research area **cuts across the full 3D-printing workflow** from custom design tools (or CAD plugins) to new printer hardware

How can we...

Enable designers to rapidly build, simulate, and fabricate **deformable** 3D-printed objects?

MAKING DEFORMABLE OBJECTS

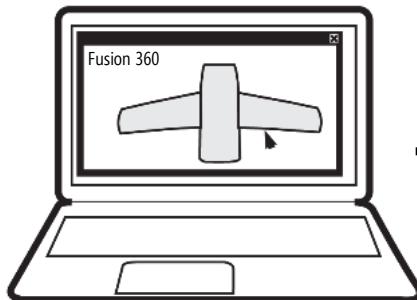
HOW TO CREATE DEFORMABLE 3D-PRINTED OBJECTS

How to design CAD tool such that users can **specify & simulate** novel deformation behaviors?

What **innovations** to the **g-code, printing hardware**, and/or **materials** might be necessary to support these deformations?
Note: typically, CS researchers in this space focus on trying to utilize commodity printing hardware with little or no changes.

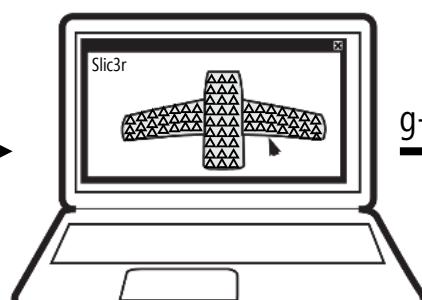
What **post-processing steps** may be required to enable the deformation (e.g., dissolve filament)?

1. DESIGNING MODELS



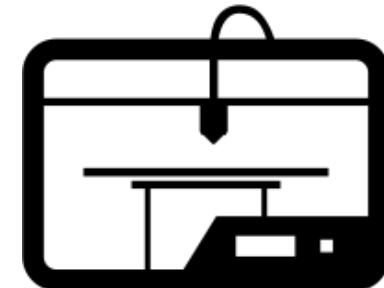
Create digital model in **CAD tool**. Export CAD model as an STL file.

2. TRANSLATING TO PRINTER CODE



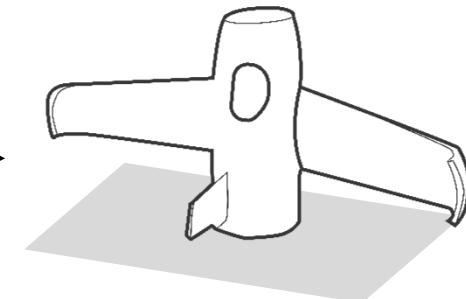
Use **slicing program** to convert STL into g-code instructions.

3. PRINTING HARDWARE & MATERIALS



Upload g-code file to 3D printer (via USB fob, WiFi) & **print!**

4. EXAMINING PRINT & POST-PROCESSING



Completed fabricated object + **post processing** (e.g., remove supports)

5. ITERATING & CREATING MORE MODELS

METAMATERIAL MECHANISMS

Metamaterial Mechanisms

Alexandra Ion, Johannes Froehhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang Ting Chen, and Patrick Baudisch
Hasso Plattner Institute, Potsdam, Germany
{firstname.lastname}@hpi.de

ABSTRACT

Recently, researchers started to engineer not only the outer shape of objects, but also their *internal microstructure*. Such objects, typically based on a regular grid, are also known as *metamaterials*. Metamaterials have been used, for example, to create materials with soft and hard regions.

So far, metamaterials were understood as materials—we want to think of them as *machines*. We demonstrate metamaterial objects that perform a mechanical function. Such *metamaterial mechanisms* consist of a single block of material cells of which play together in a well-defined way to realize a solid mechanical function. Our metamaterial door latch, for example, transforms the rotary movement of its handle into a linear motion of the latch. Our metamaterial Jansen walker consists of a single block of cells that can walk. The key element behind our metamaterial mechanisms is a specialized type of cell, the only ability of which is to shear.

In order to allow users to create metamaterial mechanisms efficiently we implemented a specialized 3D editor. It allows users to place different types of cells, including the shear cell, thereby allowing users to add mechanical functionality to their designs. To help users verify their designs during editing, our editor also users to apply forces and simulate the how the object deforms in response.

Author Keywords

metamaterial; mechanism; fabrication; 3d printing;

ACM Classification Keywords

H.5.m [Information interfaces and presentation]: Misc.

INTRODUCTION

Researchers in HCI have explored the use of personal fabrication tools, such as 3D printers [33] to help users design the exterior shape of 3D objects [16]. In order to add functionality to 3D printed objects, users can integrate electronics [28], even printed optics [37], or loudspeakers [11].

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UIST '16, October 16–19, 2016, Tokyo, Japan

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DOI: <https://doi.org/10.1145/2984511.2984540>

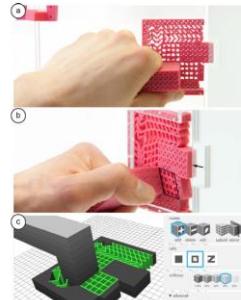


Figure 1: (a) This door latch is implemented as a metamaterial mechanism; it consists of a single block of material based on a regular grid, which contains a central hinge array, rigid members, and springs. (b) Turning the handle causes the central hinge array to deform and to pull the latch inward, which unlocks the door. (c) We created this mechanism in a custom editor.



Figure 2: The reinforced hinge in action. Note how the hinge array deforms as one while the rigid members remain undeformed. (Cells with gray tinted backgrounds are anchored to the ground, as indicated by the lock symbol. We are pushing in the direction of the arrow using the blue rod).

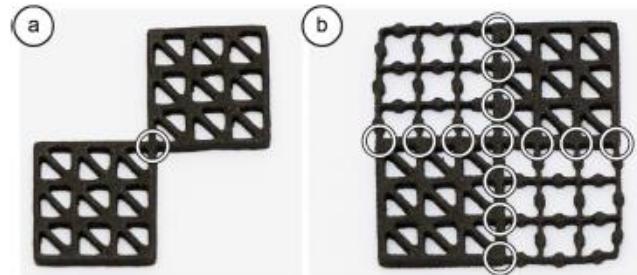


Figure 5: (a) A naïve living hinge, (b) reinforced with two arrays of hinges. To showcase the deformation, we laser cut these structures from rubber foam.

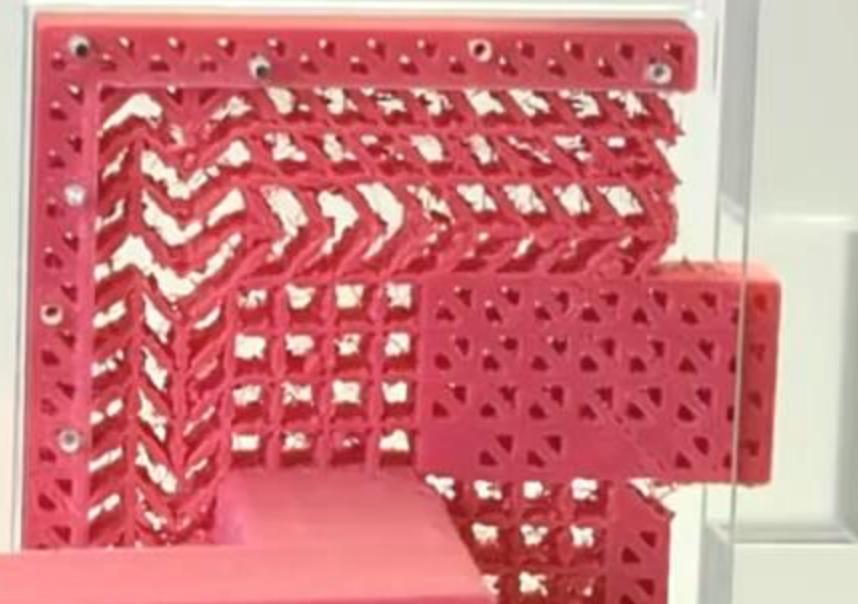
Key idea: control deformations by changing internal structure of 3D-prints

Paper contributes new CAD tool to design deformation behaviors, a new set of microstructure design primitives to specify and control deformations, and validates approach via examples

MAKING DEFORMABLE OBJECTS

METAMATERIAL MECHANISMS

**metamaterial
MECHANISMS**



Source: Ion *et al.*, UIST'16; <https://youtu.be/lstWYSfPck>

Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Daudisch

Institut



metamaterial MECHANISMS



Alexandra Ion, Johannes Frohnhofer, Ludwig Wall, Robert Kovacs, Mirela Alistar,
Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch

DIGITAL MECHANICAL METAMATERIALS

Fabricating New Materials
CHI 2017, May 6–11, 2017, Denver, CO, USA

Digital Mechanical Metamaterials
Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch
Hasso Plattner Institute, Potsdam, Germany
{firstname.lastname}@ipi.de

ABSTRACT
In this paper, we explore how to embody mechanical computation into 3D printed objects, i.e., without electronic sensors, actuators, or controllers typically used for this purpose. A key benefit of our approach is that the resulting objects can be 3D printed in one piece and they do not need assembly. We built a small 3D-printed door lock, also known as a metasensor. We introduce a new type of cell that propagates a digital mechanical signal using an embedded bistable spring. When triggered, the embedded spring discharges and the resulting impulse triggers one or more neighboring cells, resulting in a chain reaction that can be used for computation to implement simple logic functions. We demonstrate interactive objects based on this concept, such as a combination lock. We present a custom editor that allows users to model 3D objects, route signals, simulate signal flow, and synthesize cell patterns.

Author Keywords
Metamaterials; Fabrication; Programmable Matter

ACM Classification Keywords
H.5.m. [Information interfaces and presentation] Misc.

INTRODUCTION
Personal fabrication machines, such as 3D printers, allow users to make custom objects. While early work on 3D printing revolved around designing the outside of such objects [24, 32], recently researchers started exploring 3D printing as a means to design the *inside* of objects. Applications include moving objects' centers of gravity so as to make them stand [20] or spin [1].

Pushing the boundaries of creative 3D printers that consist usually of a large number of small cells arranged on a regular grid [15]. Since each cell is designed to perform a specific deformation, objects that entirely consist of such cells literally offer thousands of degrees of freedom. Such structures are also known as *metamaterials* [18].

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DOI: <http://dx.doi.org/10.1145/3025453.3026024>

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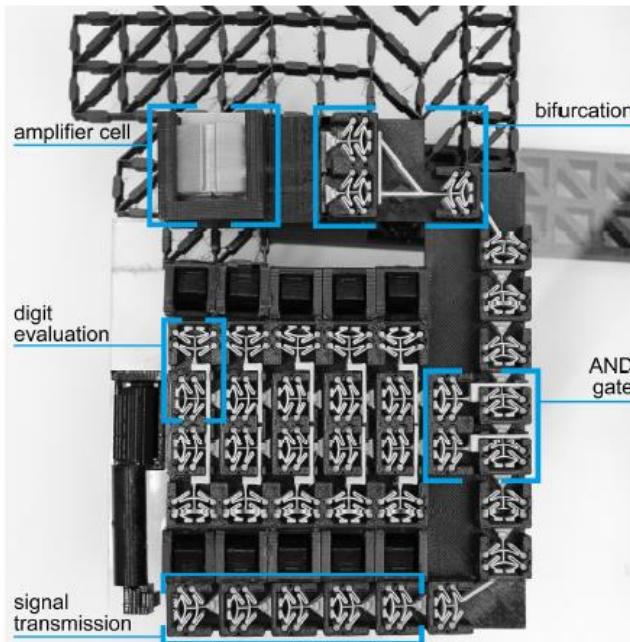


Figure 5: Our door lock consists of 82 cells, which implement the signal transmission, the evaluation of each digit input by the user, an AND gate, and one amplifier cell with a pre-amplification step to move the blocking bolts sufficiently.

Explores how to embed mechanical computation into 3D-printed objects

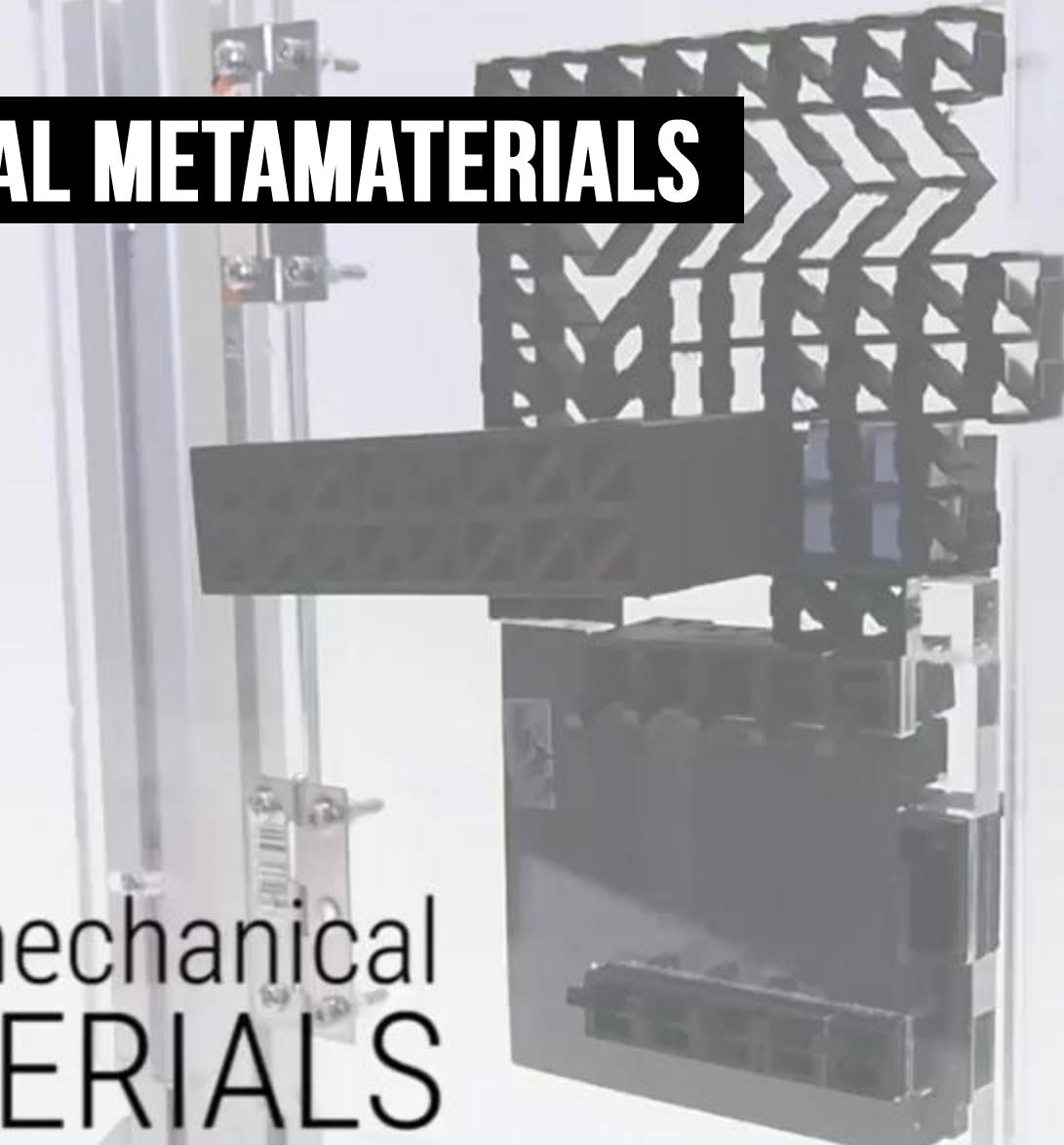
Contributes new design primitives that use bistable springs (which hold state—on or off) and can propagate a signal using impulse triggers.

Presents a modified version

MAKING DEFORMABLE OBJECTS

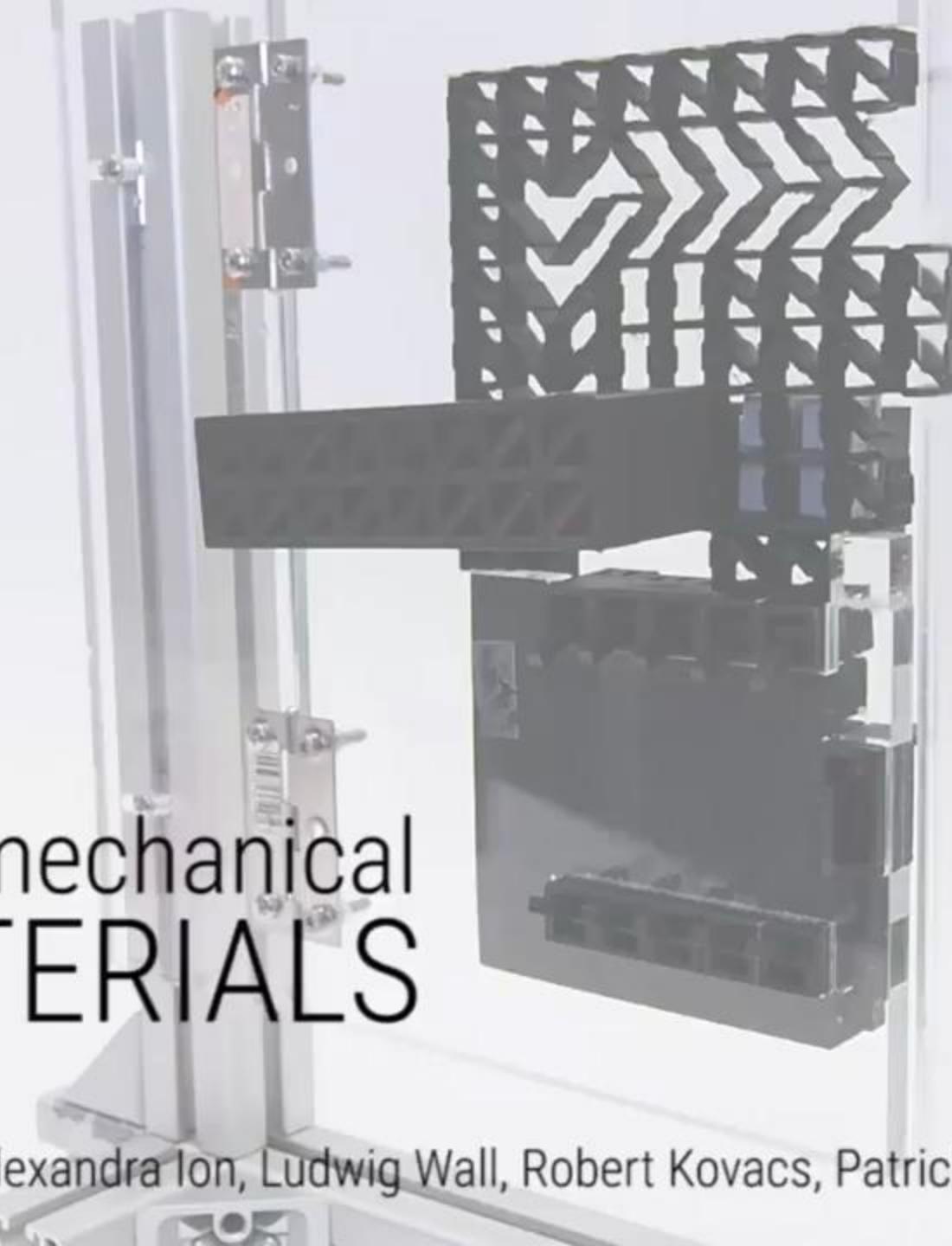
DIGITAL MECHANICAL METAMATERIALS

digital mechanical
METAMATERIALS



digital mechanical METAMATERIALS

Alexandra Ion, Ludwig Wall, Robert Kovacs, Patrick Baudisch



EMBEDDING SPRING-BASED STRUCTURES

Designing 3D-Printed Deformation Behaviors Using Spring-Based Structures: An Initial Investigation

Liang He^{1,4} Huaishu Peng³ Joshua Land² Mark D. Fuge² Jon E. Froehlich^{1,4}
¹Computer Science, ²Mechanical Engineering, Univ. of Maryland
³Information Science, Cornell University
⁴Computer Science & Engineering, University of Washington
{lianghe, jland17, fuge}@umd.edu {hp356@cornell.edu {lianghe, jonf}@cs.washington.edu

ABSTRACT
Recent work in 3D printing has focused on tools and techniques to design deformation behaviors using mechanical structures such as joints and metamaterials. In this poster, we explore how to embed and control mechanical springs to design 3D-printable objects that support an initial design space of 3D-printable spring-based structures to support a wide range of expressive behaviors, including stretch and compress, bend, twist, and all possible combinations. The poster concludes with a brief feasibility test and enumerates future work.

Author Keywords
3D printing, fabrication, deformation behaviors, design space, mechanical spring.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI). User Interfaces.

INTRODUCTION

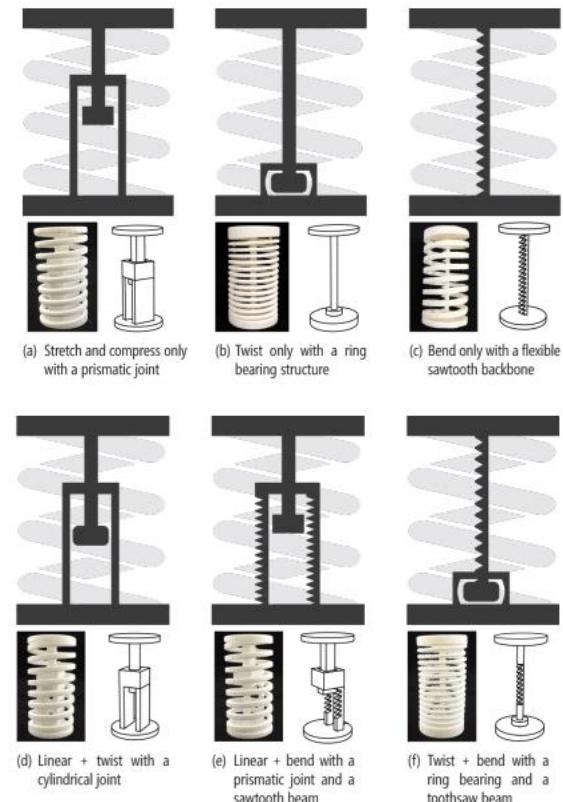
Artificial manufacturing, or 3D printing, has moved beyond simply printing the shape of a part or object. Researchers have explored imbuing 3D-printed models with mechanical properties and functions [3, 7, 8]. *Coded Skeleton* [5], for example, uses repetitive slit patterns to enable planar objects to stretch, bend and twist. *Metamaterial Mechanisms* [4] employs a lot of small parts to print with flexible beams to achieve controlled directional movements. Finally, *MechProfessor* [2] applies joint structures to creates one-off articulated models with consumer-grade 3D printers. To our knowledge, however, spring-based structures, which are one of the most widely used mechanical mechanisms, have not received commensurate attention by the 3D printing community.

In our research, we are designing and investigating tools and techniques to embed mechanical springs with controllable deformations into 3D-printed objects. We focus primarily on *helical springs* because the helix structure encapsulates *linear deflection* (stretch and compress) and *planar deflection* (bend and twist) behaviors of mechanical springs.

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Select part geometries and convert to spring-based structures

Contributes new spring-based design primitives based on helical springs such as stretch and compress, twist, and bend

Small evaluation via creation of a single model.

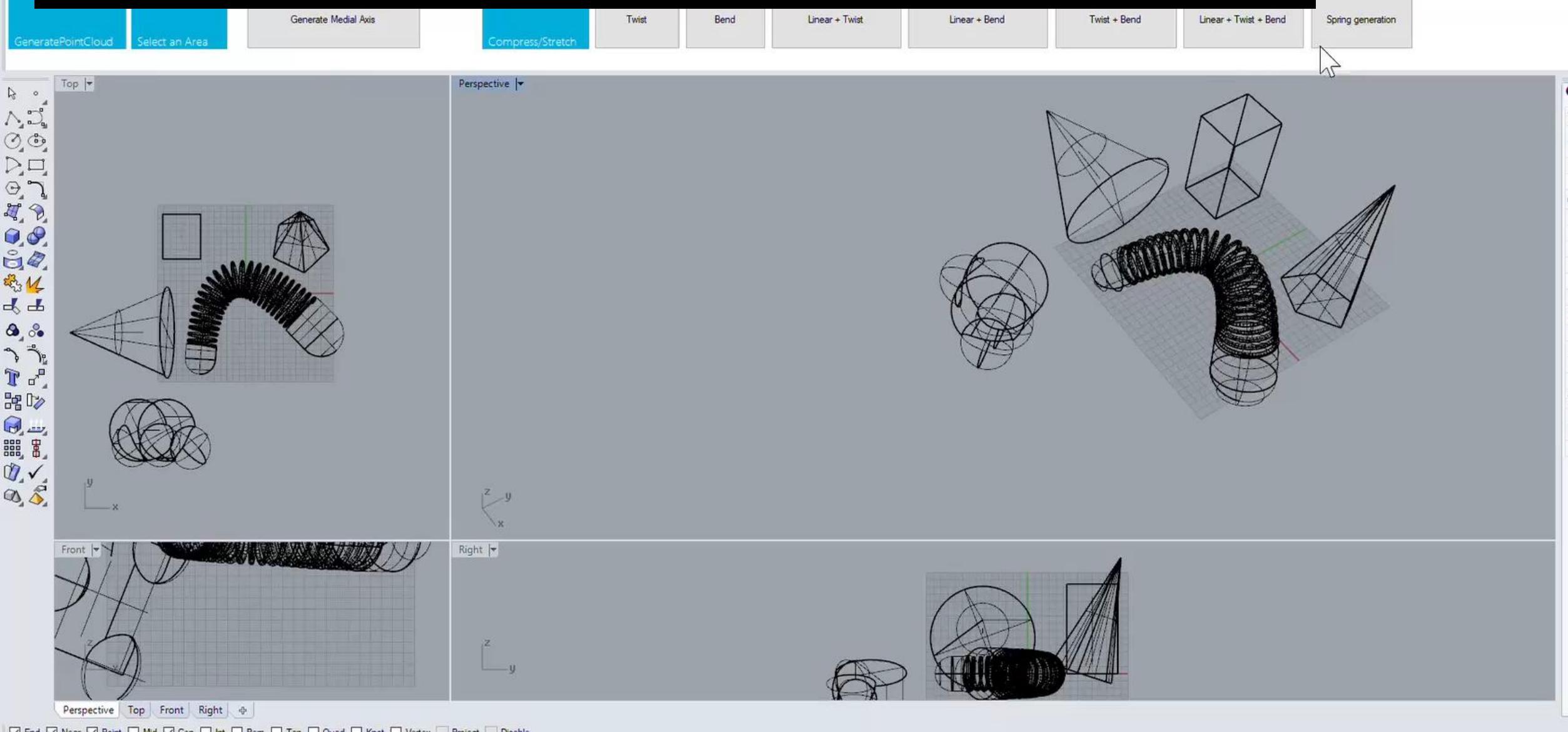
Display mode set to "Wireframe".

Select

MAKING DEFORMABLE OBJECTS

Transform Curve Tools Surface Tools Solid Tools Mesh Tools Render Tools Drafting New in

TRANSFORMING ARBITRARY GEOMETRIES TO SPRINGS



MAKING DEFORMABLE OBJECTS

PROJECT ONDULÉ: EXAMPLE DEFORMATIONS



ORIGINAL PRINT

Tigger with traditional helical spring



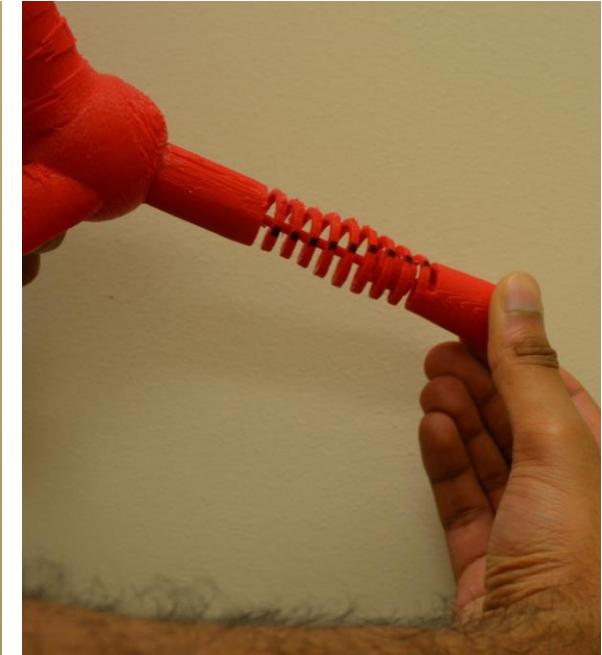
DESIGN #1: BEND ONLY

Helical spring with embedded flexible sawtooth backbone



DESIGN #2: LINEAR ONLY

Helical spring with a prismatic joint



DESIGN #3: TWIST ONLY

Helical spring with a ring bearing structure

MAKING DEFORMABLE OBJECTS

PROJECT ONDULÉ: ACCESSIBILITY APPLICATIONS



TRADITIONAL SCISSORS

Requires fine motor abilities

MAKING DEFORMABLE OBJECTS

PROJECT ONDULÉ: ACCESSIBILITY APPLICATIONS

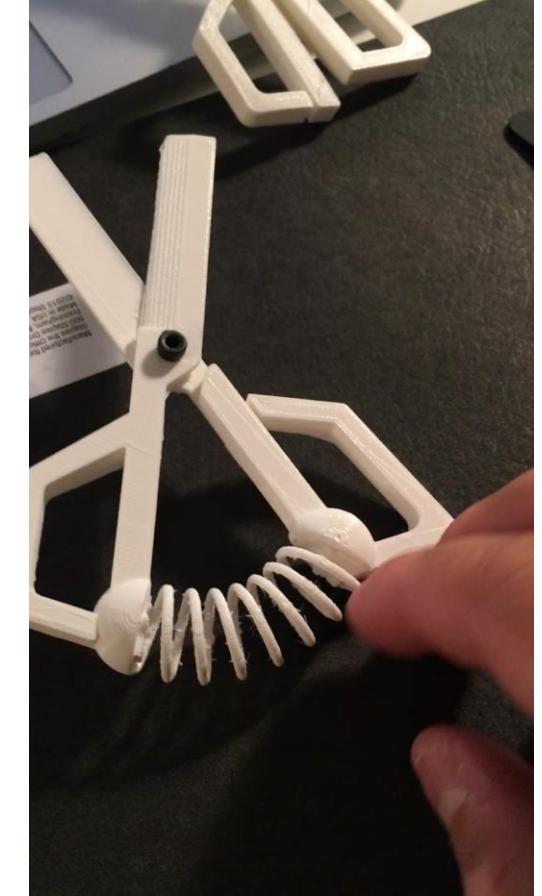


TRADITIONAL SCISSORS

Requires fine motor abilities



<http://www.handicappedequipment.org/tag/scissors-for-disabled-people/>



SPRING SCISSORS

Spring automatically reopens
scissors after a cut

TRANSFORMING STATIC MODEL TO JOINT-BASED ARTICULATED MODEL

Fabricating Articulated Characters from Skinned Meshes

Moritz Bächer
Harvard University

Bernd Bickel
TU Berlin

Doug L. James
Cornell University

Hanspeter Pfister
Harvard University

Figure 1: Given a skinned mesh (a), we estimate (b) a fabricable articulated character with (c) internal joints of hinge and ball-and-socket type. (d,e) Final 3D printed characters (transparent material) have durable joints with a frictional design for character posing.

Abstract

Articulated deformable characters are widespread in computer animation. Unfortunately, we lack methods for their automatic fabrication using modern additive manufacturing (AM) technologies. We propose a technique that takes a skinned mesh and makes a fabricatable single-material model that approximates the 3D kinematics of the corresponding virtual articulated character in a piecewise linear manner. We first extract a set of potential joint locations and then, together with open-source joint range constraints, we then estimate mechanical friction joints that satisfy inter-joint non-overlaps and other fabrication constraints. To validate our findings, we present renders on an approximate medial axis representation of the input geometry, and maximize each joint's minimal cross-sectional area. We provide several demonstrations, manufactured as single, assembled pieces using 3D printers.

Keywords: fabrication, additive manufacturing, animation, articulated solid models.

Links: [DL](#) [PDF](#)

1 Introduction

Skinned characters are among the most widespread models in computer graphics and have received tremendous attention in recent decades. Skilled artists have years of experience in creating weighted associations between a hierarchical set of bones (*rigs*) and groups of vertices on the character's mesh (*skins*). Content creation systems, such as the one built into SPINE (Hawker et al. 2008), allow even naive users to create sophisticated skinned characters.

ACM Reference Format: Bächer, M., Bickel, B., James, D., and Pfister, H. 2012. Fabricating Articulated Characters from Skinned Meshes. *ACM Trans. Graph.* 31, no. 4, Article 47 (July 2012), 10 pages.

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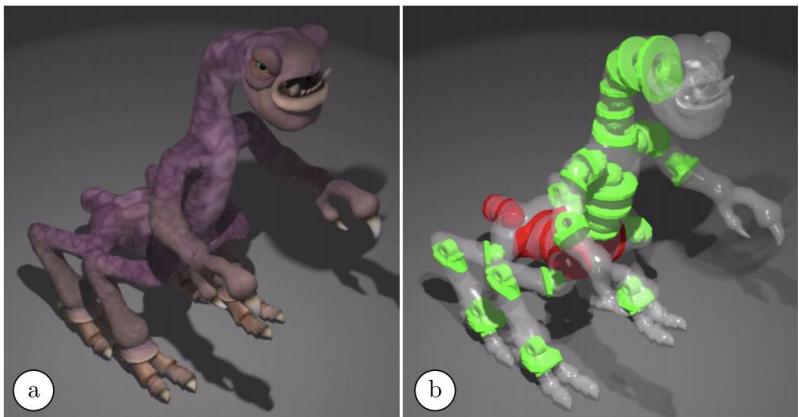


Figure 2: Virtual Rig vs. Mechanical Joints: When animating a rigged cylinder (left), we observe that the rig joints do not fall together with actual rotation centers and move out of the deformed geometry (right). If we maximize the individual sizes of mechanical joints (and thus their strength), they could collide (red).

ACM Trans. on Graphics, Vol. 31, No. 4, Article 47, Publication Date: July 2012

Takes static 3D model and automatically converts to a fabricatable single-material model with articulated motion using joints.

Contributes new algorithms for automatic conversion, optimizations that estimate mechanical friction, and provides several demonstrations for validation.

TRANSFORMING STATIC MODEL TO JOINT-BASED ARTICULATED MODEL



Joint Estimation

... estimate proxy joint locations, ...

MAKING DEFORMABLE OBJECTS

DESIGNING TELESCOPING STRUCTURES

Computational Design of Telescoping Structures

CHRISTOPHER YU, Carnegie Mellon University
KEENAN CRANE, Carnegie Mellon University
STELIAN COROS, Carnegie Mellon University

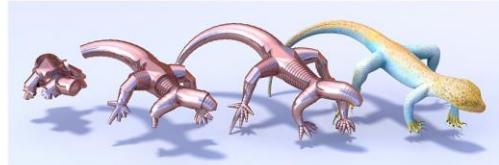


Fig. 1. A telescoping lizard in various stages of extension approximates an input surface (right). We parameterize telescoping structures as networks of smooth space curves with specific geometric properties, allowing users to rapidly explore the space of telescoping designs.

Telescoping structures are valuable for a variety of applications where mechanisms must be compact in size and yet easily deployed. So far, however, there has been no systematic study of the types of shapes that can be modeled by telescoping structures, nor practical methods for their design. We present a novel geometric characterization of telescoping curves, and explore how free-form surfaces can be approximated by networks of such curves. Our approach is based on a geometric framework that captures the dimensional impulses, which significantly generalize the linear telescopes found in typical engineering designs. Based on this principle we develop a system for exploring the space of telescoping structures. We demonstrate the wide space of telescoping structures; inputs to our system include user sketches or arbitrary meshes, which are then converted to a curve skeleton. We prototype our system with both simulated and fabricated examples, and show our system to design a variety of both simulated and fabricated examples.

CCS Concepts • Computing methodologies → Parametric curve and surface models • Applied computing → Computer-aided design

Additional Key Words and Phrases: telescoping structures, deployable structures, computational design, fabrication, discrete differential geometry

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ACM Reference format:
Christopher Yu, Keenan Crane, and Stelian Coros. 2017. Computational Design of Telescoping Structures. *ACM Trans. Graph.* 36, 4, Article #83 (July 2017), 17 pages. DOI: <http://dx.doi.org/10.1145/3075993.3075673>

1 INTRODUCTION
A pirate's telescope, consisting of straight, nested cylinders, is a familiar sight in many movies associated with tales of seafarers and explorers. The simple telescoping mechanism behind these so-called spyglasses has endured over the centuries, owing to its simple effectiveness for compact storage and rapid deployment, and is still widely used in modern engineering (Garrett and Ryan 1969; Gossard and Willford 1964). Deployable mechanisms have similarly been important in applications where an unwieldy object must be stored in or transported through a smaller vessel, e.g., large solar panels carried by space-based vessels (Stumpf 2014), or artificial structures that must travel through narrow passages in order to fit within a small package (Liu 2009). Generalized telescoping mechanisms likewise hold great promise for deployable design, providing a fundamentally new kind of joint that can be used to build complex, articulated structures with a wide range of motion.

The design of telescoping structures, however, remains largely unexplored. This paper is a first foray into mathematical and computational models for generalized telescopes and their applications.

At the most basic level, a telescoping structure consists of a sequence of nested units that can be extended and retracted. Most modern instances of such structures consist of a linear sequence of



Fig. 12. Left: Telescopes designed using our pipeline. Right: 3D printed physical prototypes.

Contributes a systematic study of the types of shapes that can be modeled by telescoping structures.

Presents novel algorithms that can convert geometry into telescoping structures

Validates approach by demonstrating a variety of examples.

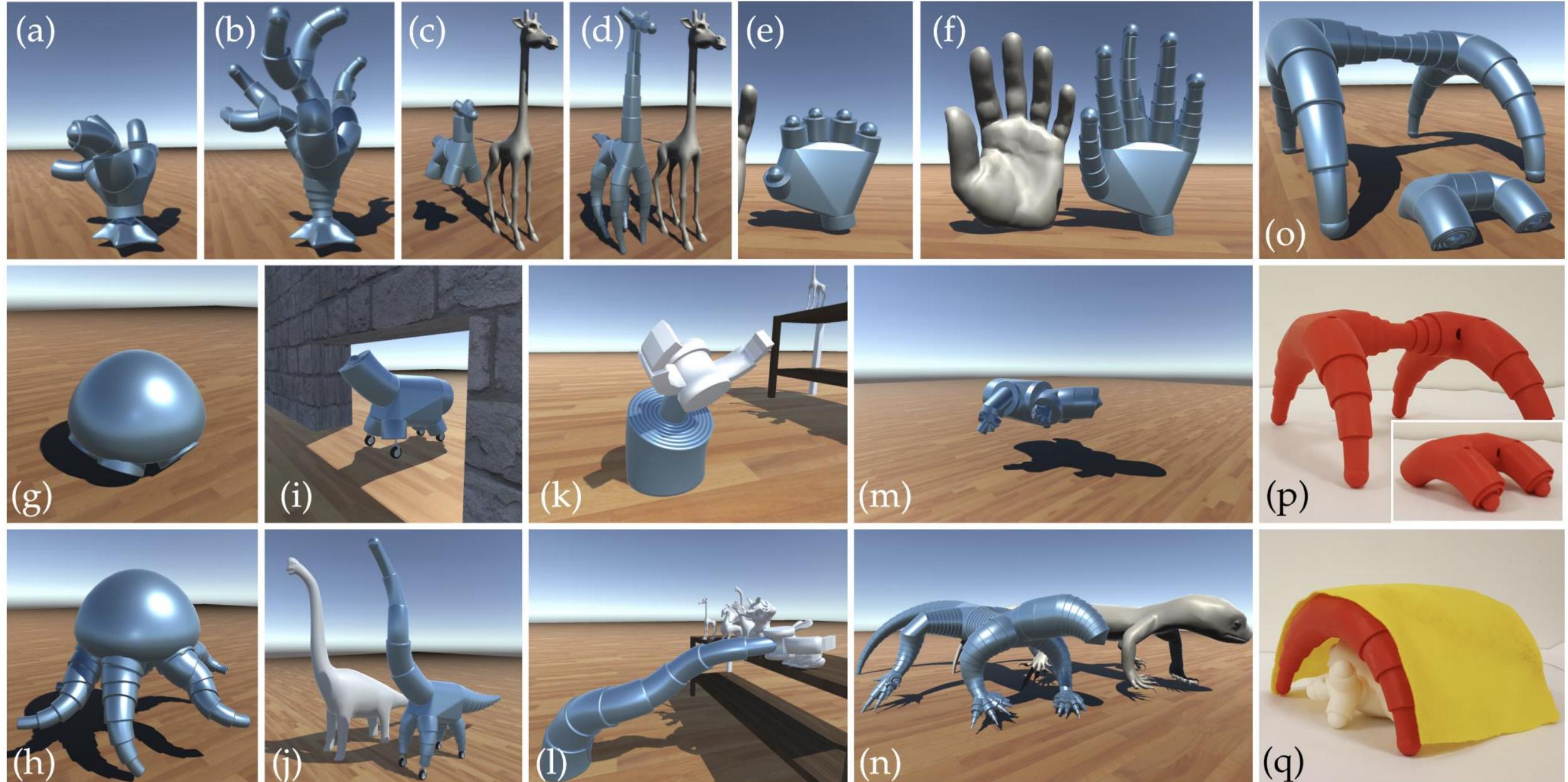
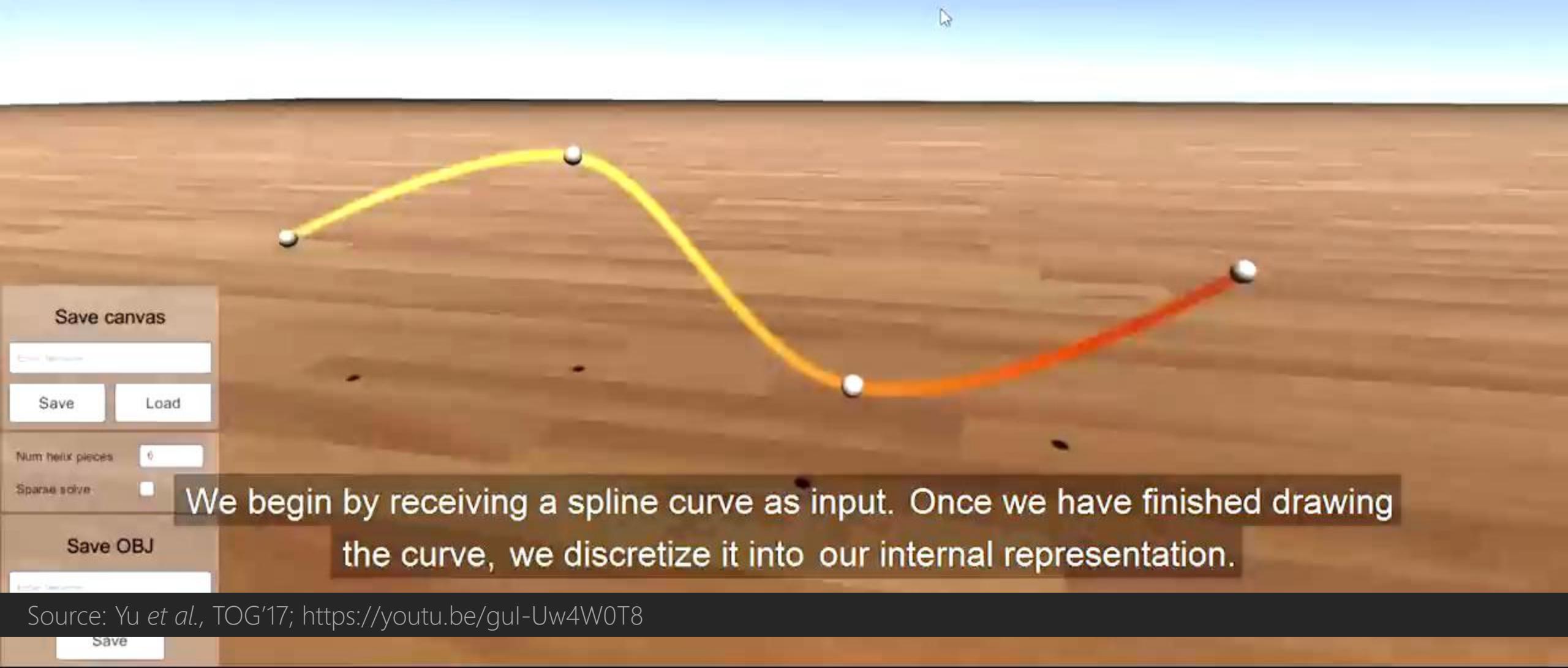
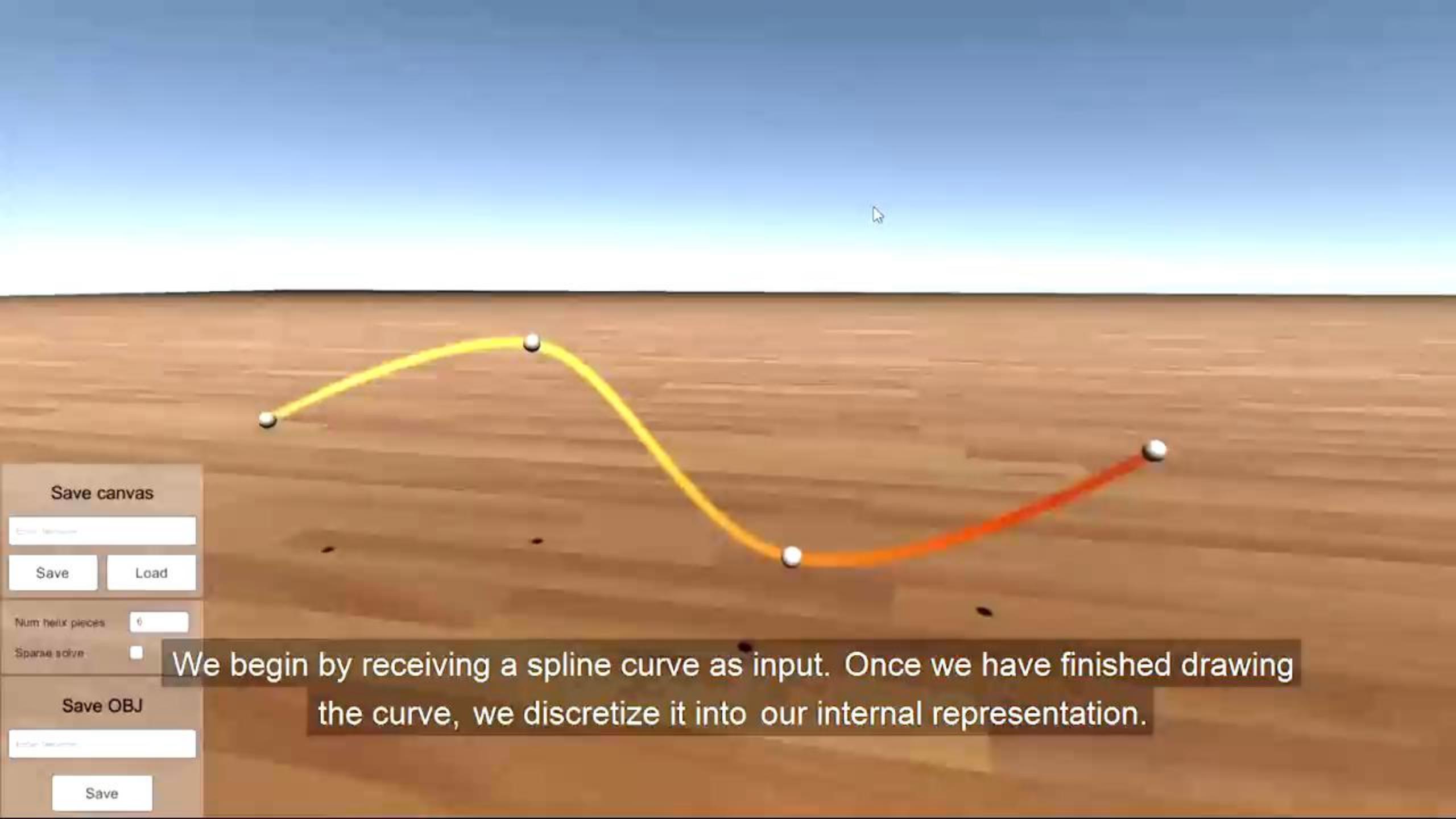


Fig. 13. Gallery of telescoping structures and applications. (a–b) Tree. (c–d) Giraffe. (e–f) Hand. (g–h) “Hexapus” with IK-driven tentacles. (i–j) Telescoping vehicular brachiosaurus. (k–l) Telescoping robotic crane driven by IK. (m–n) Lizard. (o–q) Deployable shelter housing the armadillo from Fig. 12.

DESIGNING TELESCOPING STRUCTURES

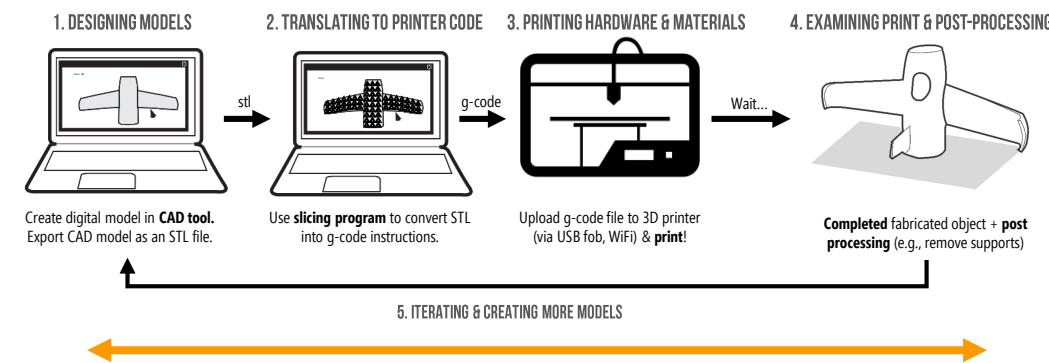


We begin by receiving a spline curve as input. Once we have finished drawing the curve, we discretize it into our internal representation.



We begin by receiving a spline curve as input. Once we have finished drawing the curve, we discretize it into our internal representation.

HOW TO CREATE KINEMATIC 3D-PRINTED OBJECTS



How can we...

Enable designers to rapidly build, simulate, and fabricate **kinematic** 3D-printed objects?

As before, this research area **cuts across the full 3D-printing workflow** from custom design tools (or CAD plugins) to new printer hardware

DESIGNING “COMPLIANT” MECHANISMS

A Computational Design Tool for Compliant Mechanisms

VITTORIO MEGARO, ETH Zurich, Disney Research
 JONAS ZEHNDER, Disney Research
 MORITZ BACHER, Disney Research
 STELIAN COROS, Carnegie Mellon University
 MARKUS GROSS, Disney Research
 BERNHARD THOMASZEWSKI, Disney Research



Fig. 1. Our computational tool for designing compliant mechanisms allows non-expert users to generate compliant versions of conventional, rigidly-articulated mechanisms. As we demonstrate with a diverse set of examples ranging from a spatial wing (left) and steering mechanism (middle) to a compliant hand well-suited for teleoperation tasks (right), our technique leads to structurally-sound and function-preserving compliant designs.

We present a computational tool for designing compliant mechanisms. Our method takes as input a conventional, rigidly-articulated mechanism and defines the new compliant mechanism. This can be both planar or spatial, and we support a number of common joint types which, whenever possible, are automatically replaced with parameterized flexures. As the task requirements change, the user can easily re-specify the motion constraints to shape the design space in a meaningful way, including trajectory matching, collision avoidance, lateral stability, resilience to failure, and avoiding smooth torques. Optimizations are based on the minimization of the design cost to equalize constrained minimization problems that we solve using a variant of sensitivity analysis. We demonstrate our method on a set of examples that range from simple four-bar linkages to full-fledged kinematics, and verify the quality of the generated compliant mechanisms by creating physical prototypes.

CCS Concepts • Computer graphics — Computational geometry and object modeling; Physically based modeling.

Additional Key Words and Phrases: Compliant Mechanism Design, Computational Design, 3D Printing.

ACM Reference Format:

Vittorio Megaro, Jonas Zehnder, Moritz Bacher, Stelian Coros, Markus Gross, and Bernhard Thomaszewski. 2017. A Computational Design Tool for Compliant Mechanisms. *ACM Trans. Graph.* 36, 4, Article #82 (July 2017), 12 pages.

<https://doi.org/10.1145/3072939.3073036>

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We are primarily interested in exploring the potential of compliant mechanisms for personalized automation and animatronics. With the ability to create complex geometry and its repertoire of flexible, plastic-like materials, 3D printing is an ideal way of manufacturing

compliant mechanisms for low-volume, one-off applications.

Source: Megaro et al., A computational design tool for compliant mechanisms, ACM Trans. Graph. 2017

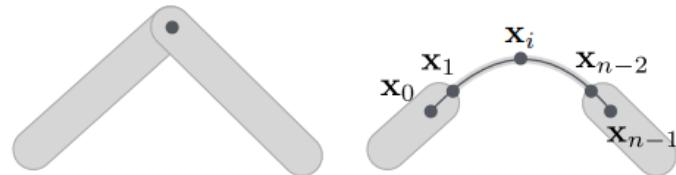


Fig. 2. Conventional vs. compliant hinge. We replace conventional joints (left) with a single or several flexures (right).

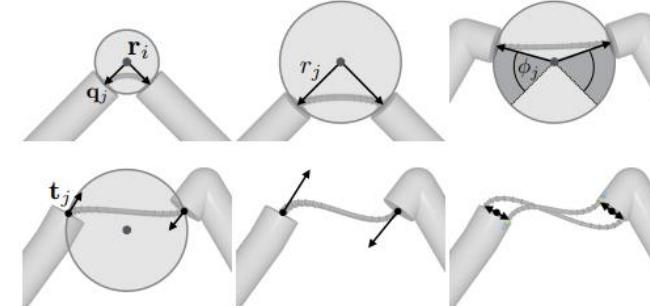


Fig. 3. Parameterizing a compliant hinge with two offset flexures.

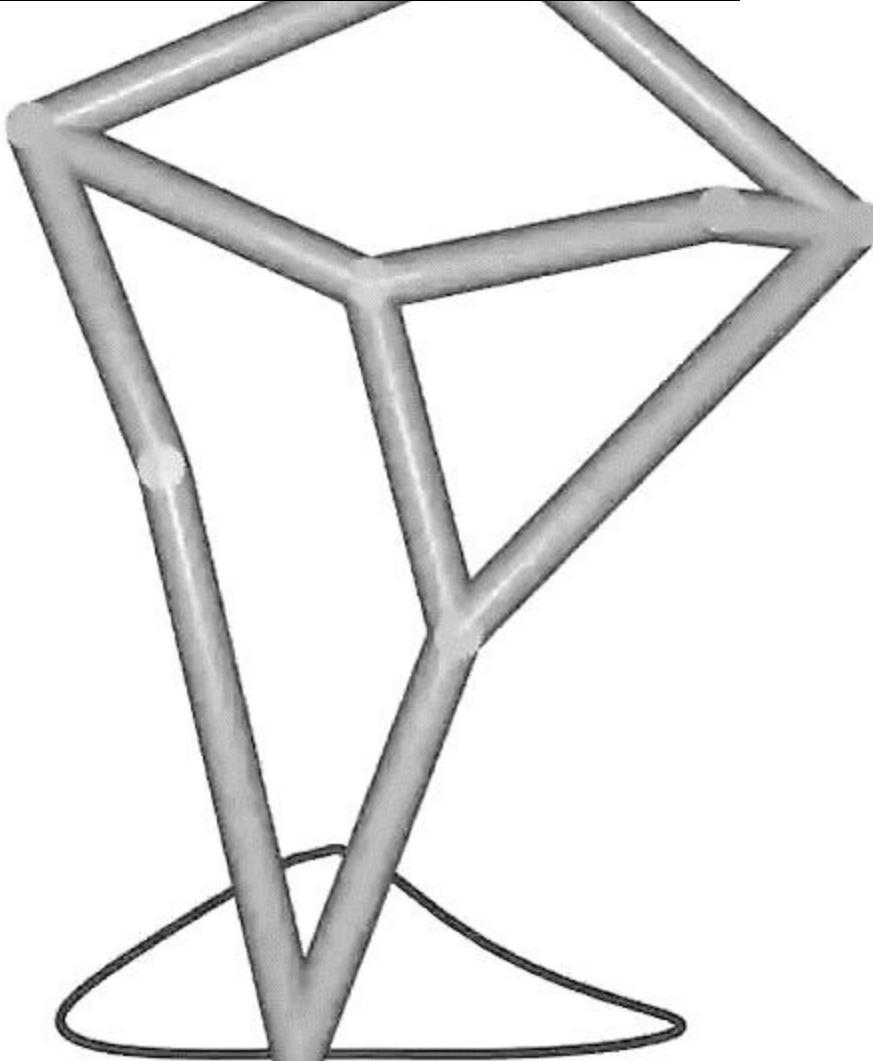
Presents a computational tool for designing compliant mechanisms to control motion behaviors.

Takes as input traditional joints (rigidly-articulated mechanisms) and converts them to parameterized flexures.

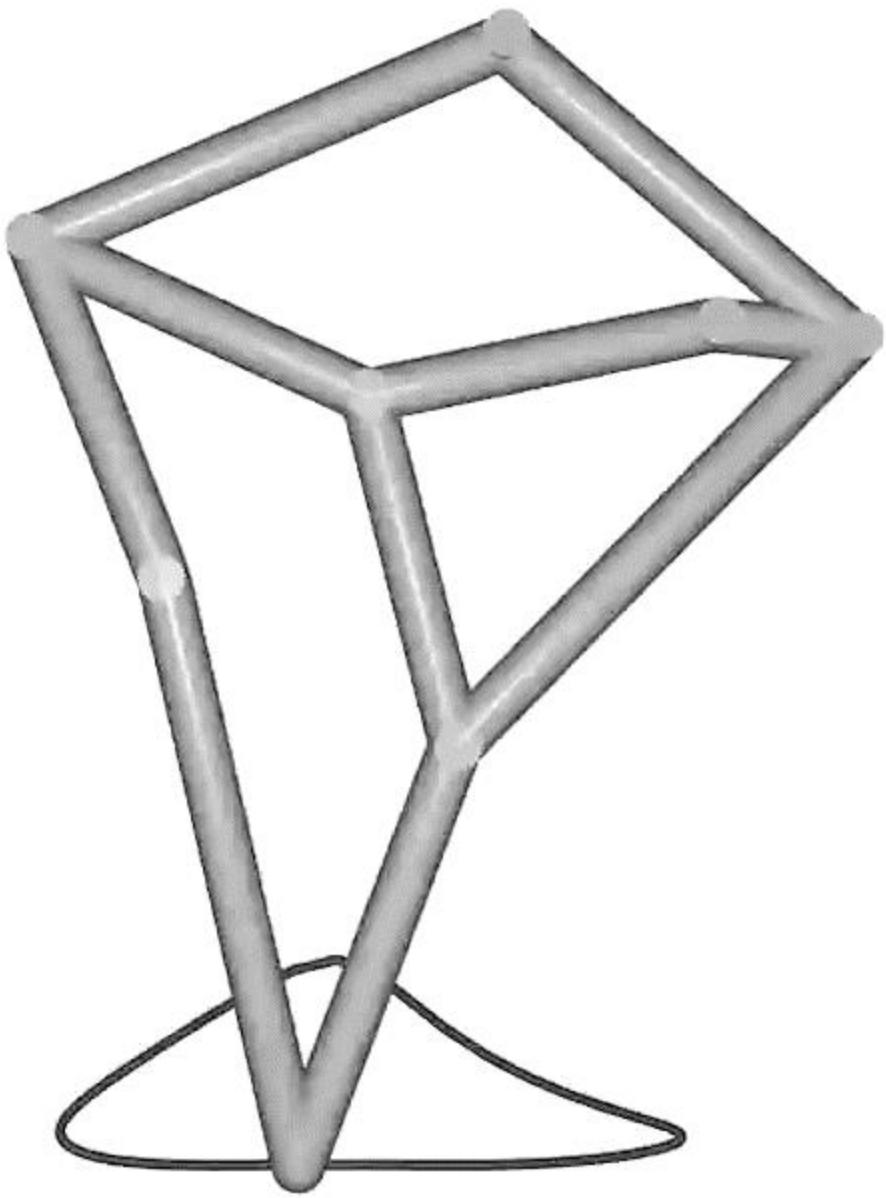
Explores design space, optimizations, resilience to failure, and verifies feasibility by creating a variety of physical prototypes.

FABRICATING MOTION

DESIGNING “COMPLIANT” MECHANISMS



Source: Megaro *et al.*, ACM Trans. Graph'17; <https://youtu.be/lUe3mGknsg4>



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DESIGNING MECHANICAL CHARACTERS

Computational Design of Mechanical Characters

Stelian Coros^{*1} Bernhard Thomaszewski^{*1} Giacomo Norti¹ Shinjiro Sueda² Moira Forberg²
 Robert W. Sumner¹ Wojciech Matusik³ Bernd Bickel¹
¹Disney Research Zurich ²Disney Research Boston ³MIT CSAIL



Figure 1: The interactive design system we introduce allows non-expert users to create complex, animated mechanical characters.

Abstract

We present an interactive design system that allows non-expert users to create animated mechanical characters. Given an articulated character as input, the user iteratively creates an animation by specifying motion curves indicating the trajectory of the character should move. For each motion curve, our framework creates an optimized mechanism that reproduces it as closely as possible. The resulting mechanisms are interconnected via gears and then connected to each other using gear trains, which are created in a semi-automated fashion. The mechanical assemblies generated with our pipeline can be driven by a hand-operated crank or an electric motor, and they can be fabricated using 3D printing. We demonstrate the versatility of our pipeline by creating several different characters, some of which we manufactured using 3D printing. While our pipeline is designed for characters driven by planar mechanisms, significant parts of it extend directly to non-planar mechanisms, allowing us to create characters with compelling 3D motions.

CR Categories: I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction Techniques; I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling

Keywords: mechanical characters, animation, fabrication, interactive design

Links: [DL](#) [PDF](#)

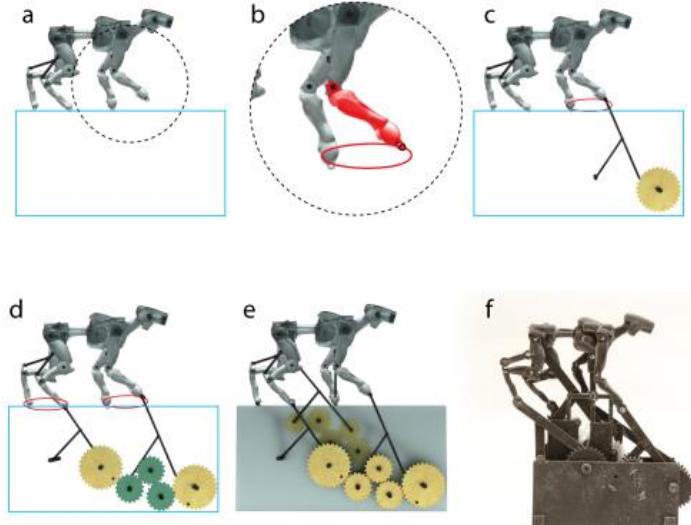
* The first two authors contributed equally.

ACM Reference Format

Coros, S., Thomaszewski, B., Guerra, R., Fiumelli, M., Sumner, R., Matusik, W., Bickel, B. 2013. Computational design of mechanical characters. *ACM Trans. Graph.* 32, 4, Article 83 (July 2013), 14 pages. DOI: <https://doi.org/10.1145/2485760.2485765>

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ACM Trans. Graph. Vol. 32, No. 4, Article 83. Publication Date: July 2013



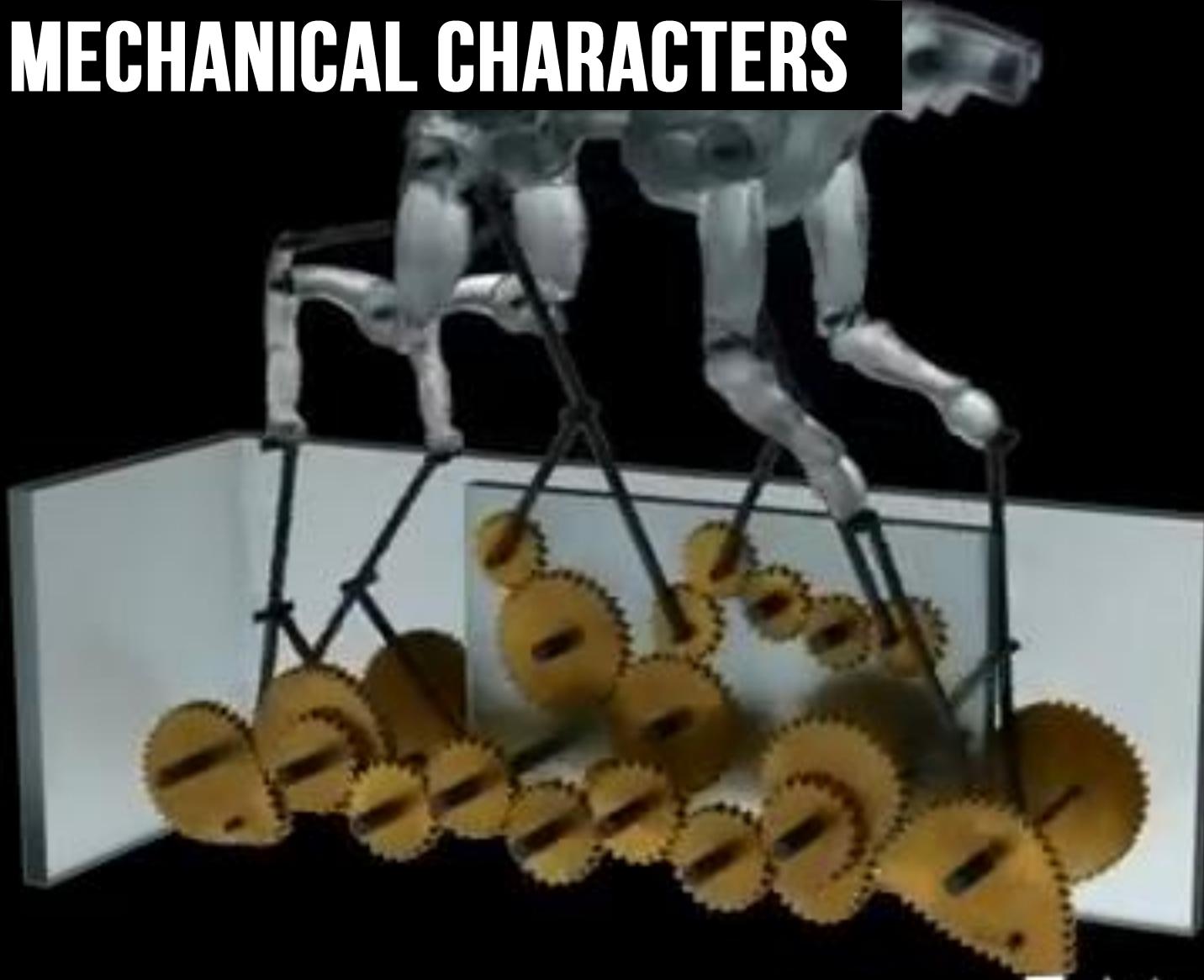
Aims to allow non-expert users to create animated mechanical characters

User specifies motion curve and tool auto-generates gear assembly to mimic motion

Contributes new design tool, interfaces and algorithms for converting motion to fabricatable gear assemblies, and a validation via demonstration

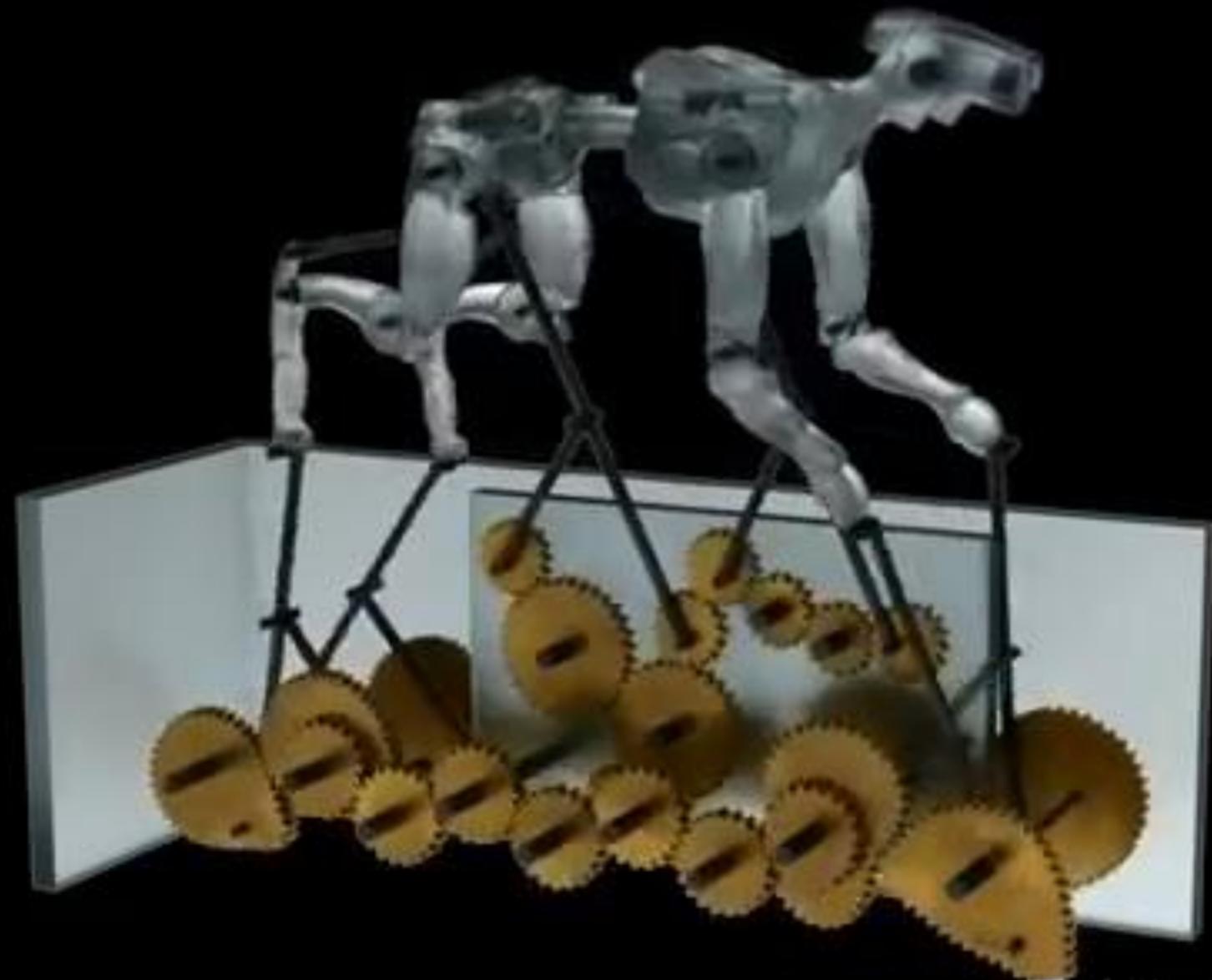
FABRICATING MOTION

DESIGNING MECHANICAL CHARACTERS



FABRICATING MOTION

Source: Coros *et al.*, ACM Trans. Graph.'13; <https://youtu.be/DfznnKUwywQ>



EMA GALOP

CREATING SPINNABLE OBJECTS

Spin-It: Optimizing Moment of Inertia for Spinnable Objects

Moritz Bächer
Disney Research Zurich
Emily Whiting
ETH Zurich
Bernd Bickel
Disney Research Zurich
Olga Sorkine-Hornung
ETH Zurich

Figure 1: We introduce an algorithm for the design of spinning tops and yo-yos. Our method optimizes the inertia tensor of an input model by changing its mass distribution, allowing long and stable spins even for complex, asymmetric shapes.

Abstract
Spinning tops and yo-yos have long fascinated cultures around the world with their unexpected, graceful motions that seemingly defy gravity. We present an algorithm to generate designs for spinning objects by optimizing rotational dynamics properties. As input, the user provides a 3D surface model and a target rotation axis. The approach then modifies the mass distribution such that the principal directions of the moment of inertia align with the target rotation axis. This is achieved by iteratively applying a local update with internal voids represented by an adaptive multi-resolution voxelization. The discrete voxel fill values are optimized using a continuous, nonlinear formulation. Further, we optimize for both the contact point and the desired spin motion. We extend our technique to incorporate deformation and multiple materials for cases where internal voids alone are insufficient. Our method is able to generate stable spins for a wide variety of objects and actors to abstract shapes. We demonstrate tops and yo-yos that spin surprisingly stably despite their asymmetric appearance.

CC Categories: I.3.3 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling
Keywords: fabrication, moment of inertia, shape optimization
Links: [DL](#) [PDF](#)

1 Introduction
Spinning tops and yo-yos have existed since antiquity as playful objects that capture the imagination. Invented independently all over the world, spinning tops are referenced in ancient Greek literature [Gould 1975], and evidence of clay tops has been found in ancient cities dating as early as 3500 B.C. Similarly, while yo-yos are believed to have been invented in China, there are many historical references, including one in the *Book of Figures* where a yo-yo spins in relative stress [Malin 1978]. Despite the long tradition of these toys, until today creating new designs has been a trial-and-error process, calling on the intuition and meticulous patience of artists and hobbyists. Moreover, there has been little debate from rotationally symmetric designs.

Much attention has been devoted in the field of classical mechanics to explaining the motion of spinning objects, however, the focus has been more on stability [Cohen 1990; Liu 1991; Cross 2012; Cross 2013] rather than design. In this paper, we investigate the unique geometric properties of shapes that spin, with an eye on designing a free-form design. A stable spin has its requirements on rotation invariant properties like precise location of the center of mass and correct alignment of the primary axes of the body. We propose an algorithm to optimize for these inertial properties and to generate stable spins that can rotate stably despite their asymmetric design.

In our approach, users provide an initial design for a spinning model, specified as a 3D surface model. Along with the input geometry, the user specifies the desired spin axis and the contact point with the support. The mass distribution is then optimized to ensure that the primary axis for the moment of inertia aligns with the desired axis of rotation. Since the contact area depends on the orientation of the body, we project it on the surface geometry, we preserve the appearance of the input design by prioritizing changes to the internal mass distribution. The algorithm starts with a coarse voxel grid to remove large unfavorable voids in cases where internal modifications are not sufficient. Alternatively, we can optimize dual-material models that compensate unfavorable configurations with a higher density fill, avoiding changes to the external shape.

Overall, we present a novel technique to design objects with specific dynamic properties and make the following contributions: We formulate a motion planning function that takes a 3D surface model of a solid shape about a user-defined axis. Using this function, we derive constraint optimization problems that align the principal axes for moment of inertia with user-specified rotations. To this end, we minimize the rate of precession moment in the contact and lateral directions and place the center of mass on the rotation axis.

ACM Reference Format:
Bächer, M., Whiting, E., Bickel, B., Bäcker-Horschung, O. 2014. Spin-It: Optimizing Moment of Inertia for Spinnable Objects. *ACM Trans. Graph.* 33, No. 4, Article 96 (July 2014), 11 pages.

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DOI: <http://dx.doi.org/10.1145/2601097.2601107>

ACM Transactions on Graphics, Vol. 33, No. 4, Article 96, Publication Date: July 2014



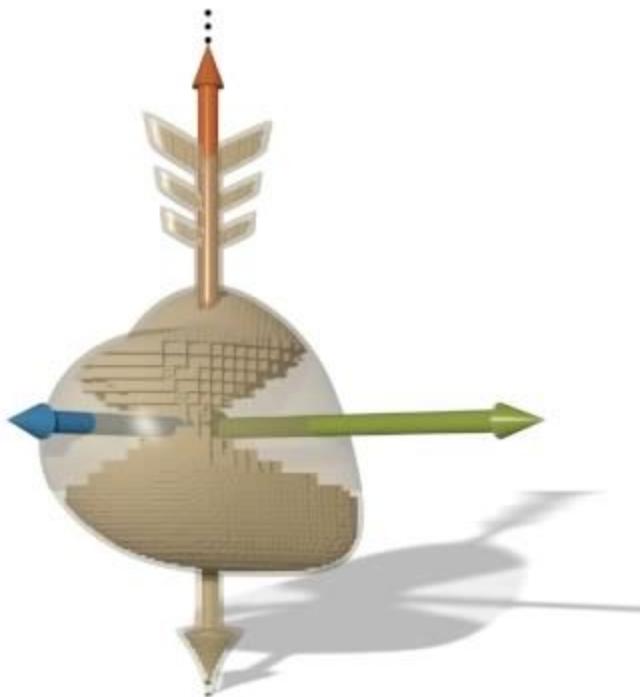
Figure 9: “Teapot”: (Left) Hollowed result showing voxelized interior mass and aligned axes using $f_{top} = f_{yo-yo}$. (Middle) Lowering of the center of mass shifts the mass distribution closer to the contact point. If we include mass reduction (right), mass is reduced inward out, resulting in the design with highest rotational stability.

Contributes new algorithms to change the infill properties of a model in order to optimize rotational dynamics

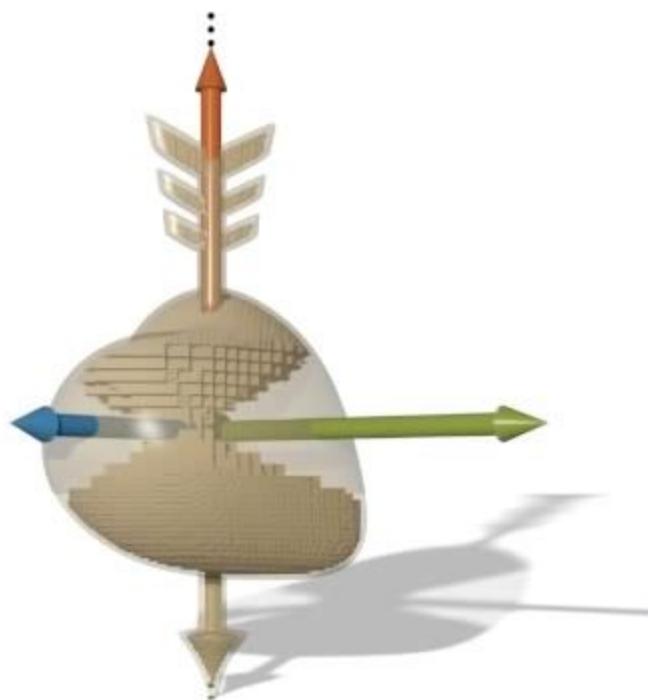
Validates approach via demonstration of models converted to tops and yo-yos

CREATING SPINNABLE OBJECTS

optimized result

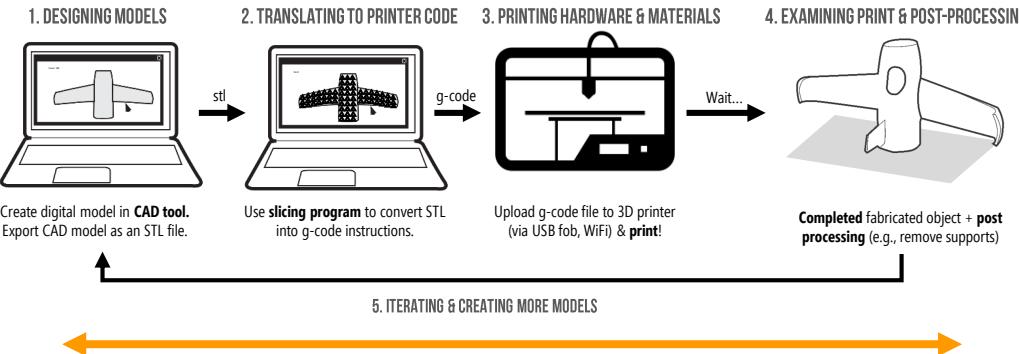


optimized result



All of the aforementioned research was on trying to make 3D-printed objects deformable or movable in predictable ways. How can we make **3D-printed objects digitally interactive** (*i.e.*, designing new digital-physical experiences)?

HOW TO CREATE DIGITALLY INTERACTIVE OBJECTS?



This research area **cuts across the full 3D-printing workflow** from custom design tools (or CAD plugins) to new printer hardware

How can we...

Enable designers to rapidly build, simulate, and fabricate **digitally interactive** 3D-printed objects?

FABRICATING INTERACTIVE ELECTROMAGNETIC DEVICES

A 3D Printer for Interactive Electromagnetic Devices

Huaishu Peng^{1,2} François Guimbretière^{1,2} James McCann¹ Scott E. Hudson^{1,3}

Disney Research Pittsburgh¹ Computing and Information Science² HCI Institute³
Pittsburgh, PA 15213 Cornell University Ithaca, NY 14850 Carnegie Mellon University
jmcann@disneyresearch.com {hp356, fvg3}@cornell.edu Pittsburgh, PA 15213
scott.hudson@cs.cmu.edu



Figure 1. 3D printed electromagnetic devices: a) Solenoid used to actuate the cat band; b) A Ferrofluid display; c) A movement sensor based on coupling strength; d) The stator and the rotor of a reluctance motor. The electromagnetic components are printed with a soft iron core, wound in place, and multiple layer of copper wire.

ABSTRACT
We introduce a new form of low-cost 3D printer to print interactive electromechanical objects with *in place* printing. At the heart of this printer is a mechanism for depositing wire within a five degree of freedom (5DOF) fused deposition modeling (FDM) 3D printer. Copper wire can be used with thin insulation to form coils which can be used as actuators or sensors. Soft iron wire can additionally be used to form components with high magnetic permeability which are then able to shape and direct these magnetic fields to where they are needed. When fabricated with structural plastic elements, this allows simple electromechanical components to be directly 3D printed. As examples, we demonstrate the fabrication of a solenoid actuator for the arm of a *Lucky Cat* figurine, a 6-pole motor stepper stator, a reluctance motor rotor and a Ferrofluid display. In addition, we show how printed coils which generate small currents in response to user actions can be used as input sensors in interactive devices.

Author Keywords
3D printing; computational crafts; electromagnets; rapid prototyping; interactive devices; fabrication.

ACM Classification Keywords
I.3.6 Information Interfaces and Presentation (e.g. HCI); I.6.10 Miscellaneous

INTRODUCTION
3D printing technology has moved beyond simply instantiating 3D geometries to printing functional and interactive objects. Recent work has considered how a range of functional objects might be fabricated, including 3D printed sensors [1], 3D printed actuators [2], 3D printed robots [14], and pneumatic devices for haptic feedback [28]. By using conductive filament, ink, or fabric sheets, several projects also explored embedding three-dimensional conductive traces into objects to create simple electronic devices [24, 29, 17]. This opens up the possibility of eventually using 3D printing for the on-demand fabrication of highly custom interactive devices, as well as greatly expanding our ability to rapidly prototype sophisticated devices. However, to date we have not been able to directly print functional electromechanical components needing actuators, but instead these required either assembly with, or pre-manufactured parts into a printer.

In this paper, we introduce a new type of 3D printer that can print interactive objects with embedded electromagnetic coil components such as those illustrated in Figure 1, including a solenoid actuator for the arm of a *Lucky Cat* figurine (Figure 1a), a Ferrofluid display (Figure 1b), an electromagnetic input sensor (Figure 1c), and both the stator and rotor for an

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DOI: <http://dx.doi.org/10.1145/2984511.2984523>

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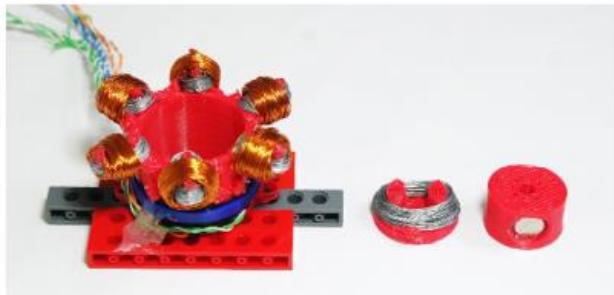


Figure 10. 3D printed motor elements: Left: stator with 6 poles; middle: a reluctance rotor printed on our printer; Right a magnet holder rotor (the magnets were not printed).

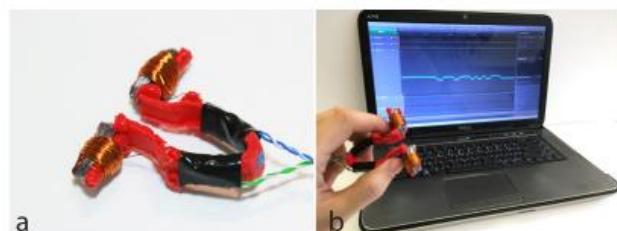


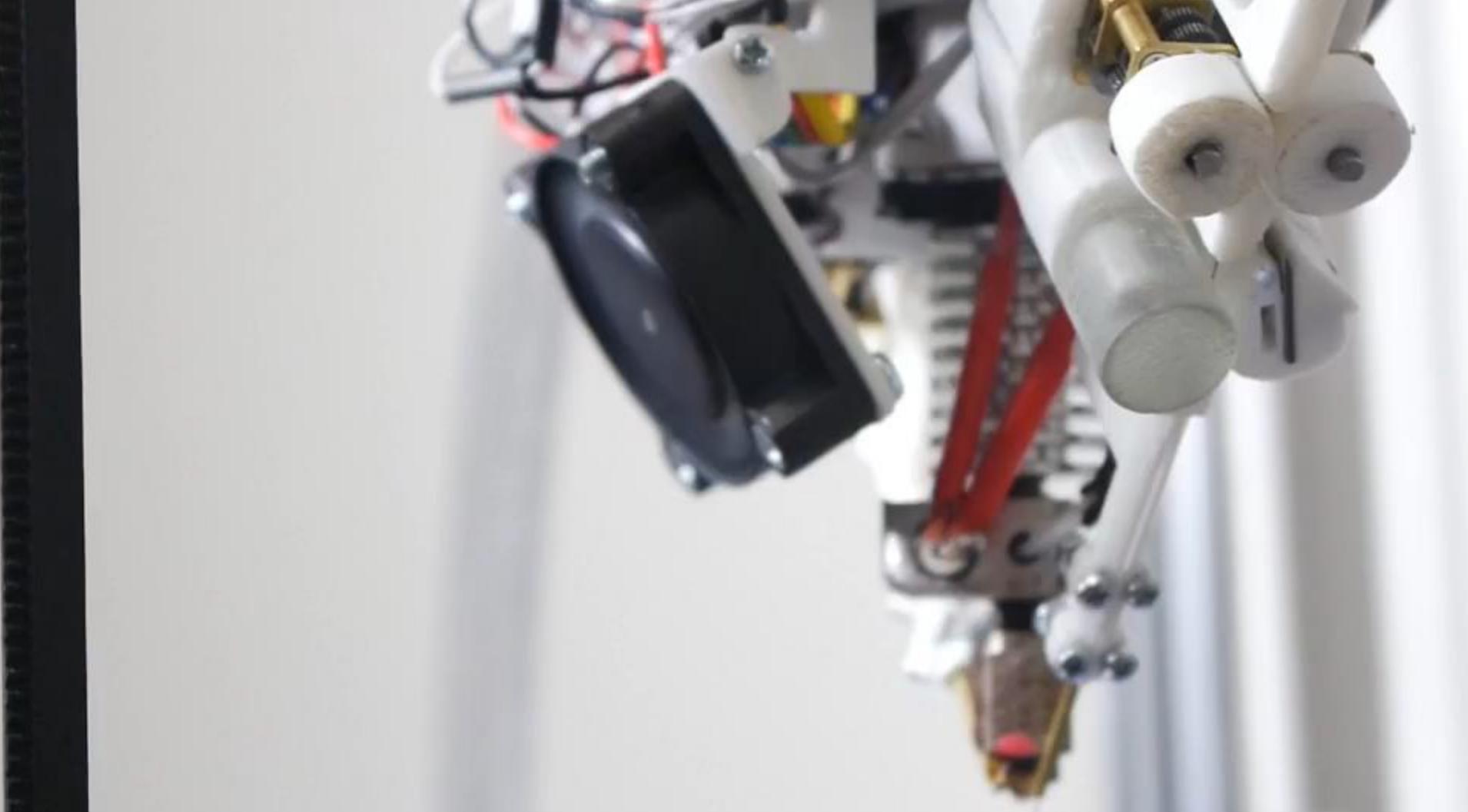
Figure 12. A printed coupling sensor. a) The sensor is made by printing two coils next to each other; b) By driving one coil with a square wave, we can infer distance between the two coils by observing the coupling strength.

New fabrication pipeline (CAD + 3D printer) to print interactive electromechanical objects.

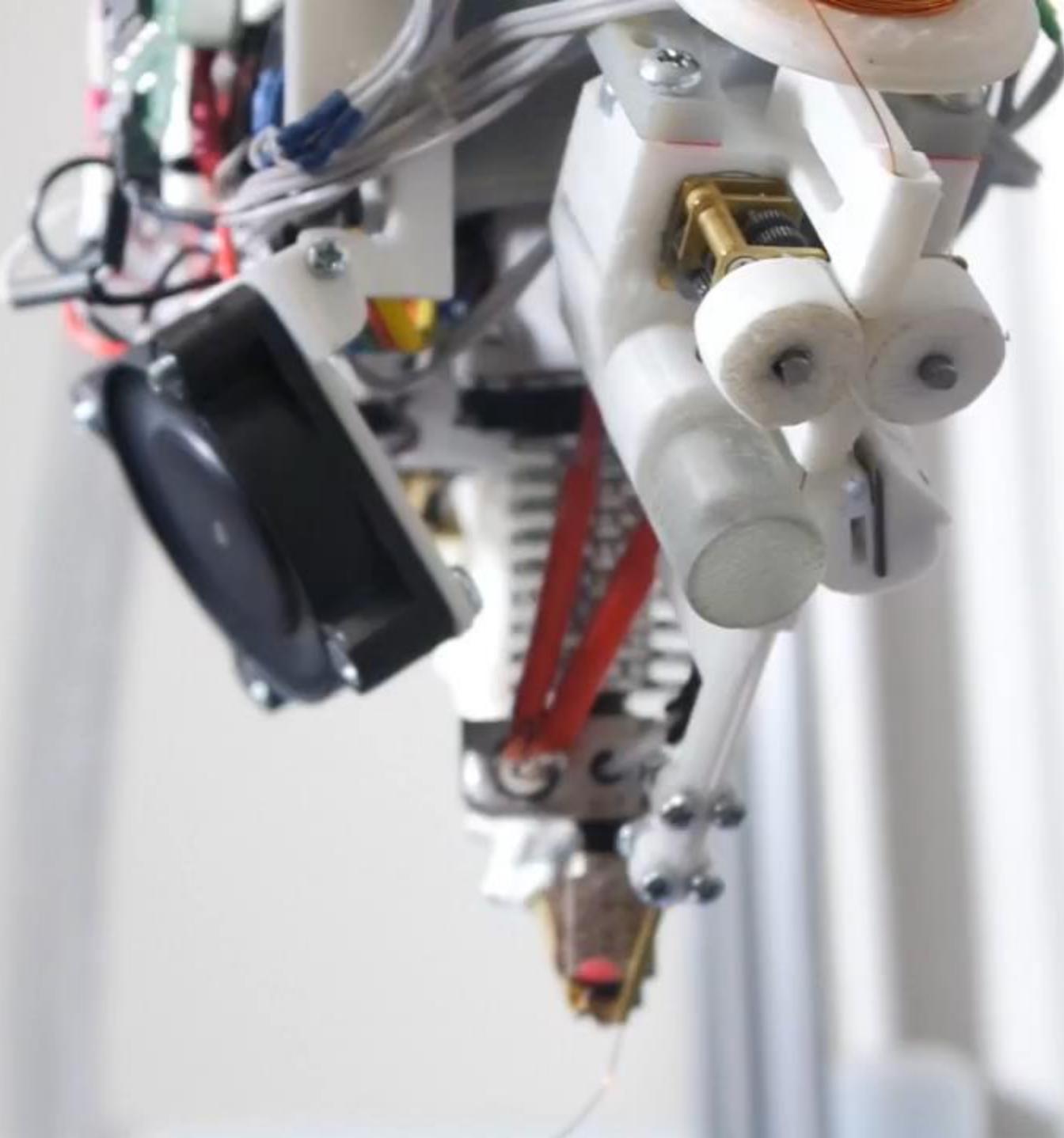
Validates approach via creation of multiple different models and electromechanical interactions.

FABRICATING INTERACTIVE DIGITAL-PHYSICAL OBJECTS

FABRICATING INTERACTIVE ELECTROMAGNETIC DEVICES



Source: Peng *et al.*, UIST'16; <https://youtu.be/EeljtHu-Luc>



3D-PRINTED, EMBEDDED OPTICS FOR INTERACTIVE DEVICES

Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices

Karl D.D. Willis^{1,2}
Disney Research Pittsburgh¹
Pittsburgh
PA 15213
{karl, eric.brockmeyer, iivan.poupyrev}@disneyresearch.com

Eric Brockmeyer¹

Pittsburgh

PA

15213

{karl,

eric.

brockmeyer,

iivan.

poupyrev}

@disneyresearch.com

Scott E. Hudson^{1,3}
Computational Design Lab², HCI Institute³
Carnegie Mellon University¹
5000 Forbes Avenue
Pittsburgh, PA 15213
scott.hudson@cs.cmu.edu

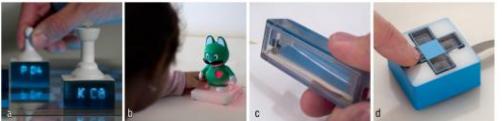


Figure 1: Custom optical elements are fabricated with 3D printing and embedded in interactive devices, opening up new possibilities for interaction including: unique display surfaces made from 3D printed ‘light pipes’ (a), novel internal illumination techniques (b), custom optical sensors (c), and embedded optoelectronics (d).

ABSTRACT

We present an approach to 3D printing custom optical elements for interactive devices labelled *Printed Optics*. *Printed Optics* enable sensing, display, and illumination elements to be 3D printed directly into the mechanical structure of an interactive device. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be designed and embedded for individual users, rapidly prototyping interactive devices. *Printed Optics* is part of our long term vision for interactive devices that are 3D printed in their entirety. In this paper we explore the possibilities for this vision afforded by fabrication of custom optical elements using today’s 3D printing technology.

ACM Classification: H.5.2 [Information Interfaces and Presentation]: User Interfaces.

Keywords: 3D printing; optics; light; sensing; projection; display; rapid prototyping; additive manufacturing.

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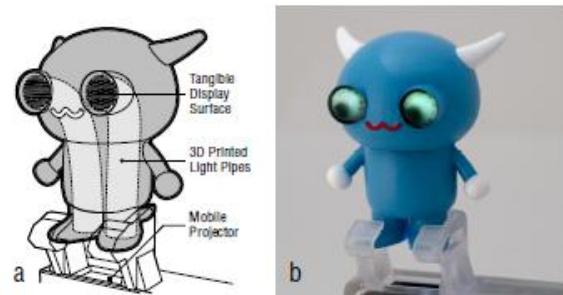


Figure 3: A 3D printed mobile projector accessory using embedded light pipes (a) to map a projected image onto a character's eyes (b).

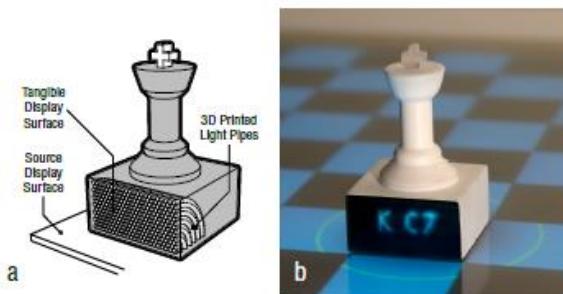


Figure 5: Light pipes are 3D printed inside tangible objects, such as chess pieces (a), to create additional display surfaces for tabletop interaction (b).

Presents new approach to 3D printing custom optical elements for interactive devices

Using printed optics, unique display surfaces, novel illumination, custom optical sensors, etc. can be rapidly fabricated and customized.

Validates method via examples

FABRICATING INTERACTIVE DIGITAL-PHYSICAL OBJECTS

3D-PRINTED, EMBEDDED OPTICS FOR INTERACTIVE DEVICES



Source: Willis *et al.*, UIST'12; <https://youtu.be/eTeXTbXA6-Y>



INTERACTIVITY VIA CORRUGATED TUBES & AIR PULSES

Demos and Posters
TEI 2017, March 20–23, 2017, Yokohama, Japan

Squeezapulse: Adding Interactive Input to Fabricated Objects Using Corrugated Tubes and Air Pulses

Liang He¹ ^{*}Gérald Laput² Eric Brockmeier³ Jon E. Froehlich¹
¹University of Maryland, College Park, Maryland, United States
²Carnegie Mellon University, Pittsburgh, Pennsylvania, United States
^{*}{lianghe, jonf}@cs.umd.edu, ²gerald.laput@cs.cmu.edu, ³ebrockme@andrew.cmu.edu



Figure 1. We introduce Squeezapulse, a technique for creating interactive fabricated objects using acoustic sensing without external circuitry or power but one single microphone. Above, four example applications show the flexibility and value of our approach: (a) a gamepad controller; (b) a soft and interactive bunny; (c) a squeezable phone case; and (d) a force sensor.

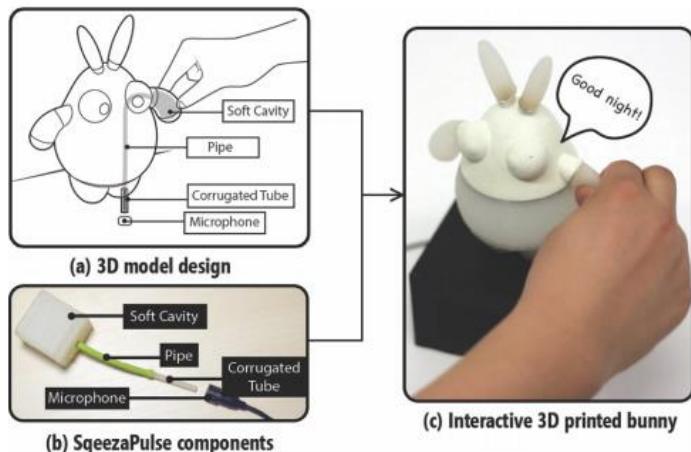
ABSTRACT
We present Squeezapulse, a technique for embedding interactive functionality into low-cost, 3D-printed objects using passive acoustic sensing and air pulses. When a soft cavity is squeezed, air pulses travel along a flexible pipe and into a uniquely designed corrugated tube that shapes the airflow into predictable sound signatures. Microphone captures and identifies these air pulses to enable interactive functionality. We describe an informal examination of the effect to different 3D-printed corrugations on air signatures, and our resulting Squeezapulse implementation. To demonstrate and evaluate Squeezapulse, we conducted a user study involving 10 users across applications and a small, lab-based user study ($N=9$). Our evaluations show that our approach is accurate across users and robust to external noise. We conclude with a discussion of limitations and future work.

Author Keywords
Fabricated objects, passive acoustic sensing, soft cavity, pipe, air pulse, interactions; corrugated tube; air pulse.

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI); Input devices and strategies.

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DOI: <https://doi.org/10.1145/3024976>

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Technique for embedding interactivity into fabricated objects using soft, passive, and low-cost bellow-like structures.

Soft cavity is squeezed, air pulses travel along a flexible pipe with a uniquely designed 3D-printed corrugated tube that shapes the airflow into predictable sound signatures.

Validated via a user study and example demonstrations

FABRICATING INTERACTIVE DIGITAL-PHYSICAL OBJECTS

INTERACTIVITY VIA CORRUGATED TUBES & AIR PULSES



Source: He *et al.*, TEI'17; <https://youtu.be/wmBz1dl1nC8>



3D-PRINTING PLASTICS + CONDUCTIVE INK

Journal List > J Vis Exp > (58), 2011 > PMC3346051

jove Journal of Visualized Experiments
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J Vis Exp. 2011; (58): 3189. doi: 10.3791/1189
 Published online 2011 Dec 9. PMID: 22214973
 PMCID: PMC3346051
 PMID: 22214973

Planar and Three-Dimensional Printing of Conductive Inks
 Bok-Yeop Ahn, Steven B. Walker, Scott C. Slimmer, Analisa Russo, Ashley Gupta, Steve Kranz, Eric B. Duoss, Thomas F. Malkowski, and Jennifer A. Lewis
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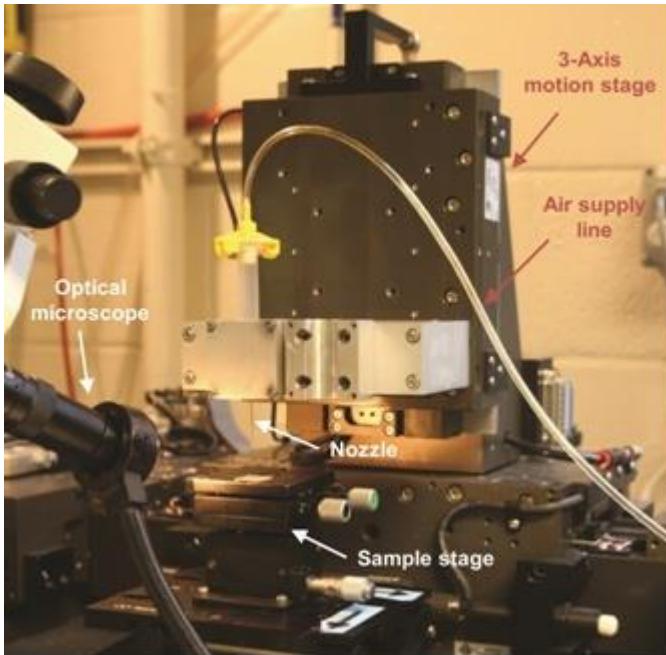
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Abstract Go to: ↴
 Printed electronics rely on low-cost, large-area fabrication routes to create flexible or multidimensional electronic, optoelectronic, and biomedical devices^{1–3}. In this paper, we focus on one- (1D), two- (2D), and three-dimensional (3D) printing of conductive metallic inks in the form of flexible, stretchable, and spanning microelectrodes.
 Direct-write assembly^{4,5} is a 1-to-3D printing technique that enables the fabrication of features ranging from simple lines to complex structures by the deposition of concentrated inks through fine nozzles (~0.1 – 250 µm). This printing method consists of a computer-controlled 3-axis translation stage, an ink reservoir and nozzle, and 10x telescopic lens for visualization. Unlike inkjet printing, a droplet-based process, direct-write assembly involves the extrusion of ink filaments either in- or out-of-plane. The printed filaments typically conform to the nozzle size. Hence, microscale features (< 1 µm) can be patterned and assembled into larger arrays and multidimensional architectures.
 In this paper, we first synthesize a highly concentrated silver nanoparticle ink for planar and 3D printing via direct-write assembly. Next, a standard protocol for printing microelectrodes in multidimensional motifs is demonstrated. Finally, applications of printed microelectrodes for electrically small antennas, solar cells, and light-emitting diodes are highlighted.

Keywords: Bioengineering, Issue 58, Direct-write assembly, silver ink, 3D printing, planar, three-dimensional, microelectrodes, flexible electronics, printed electronics



Download video file. (68M, mov)



Directly 3D-printing conductive materials is challenging: high-conductivity materials have to be extruded at high temperatures, which melts plastic.

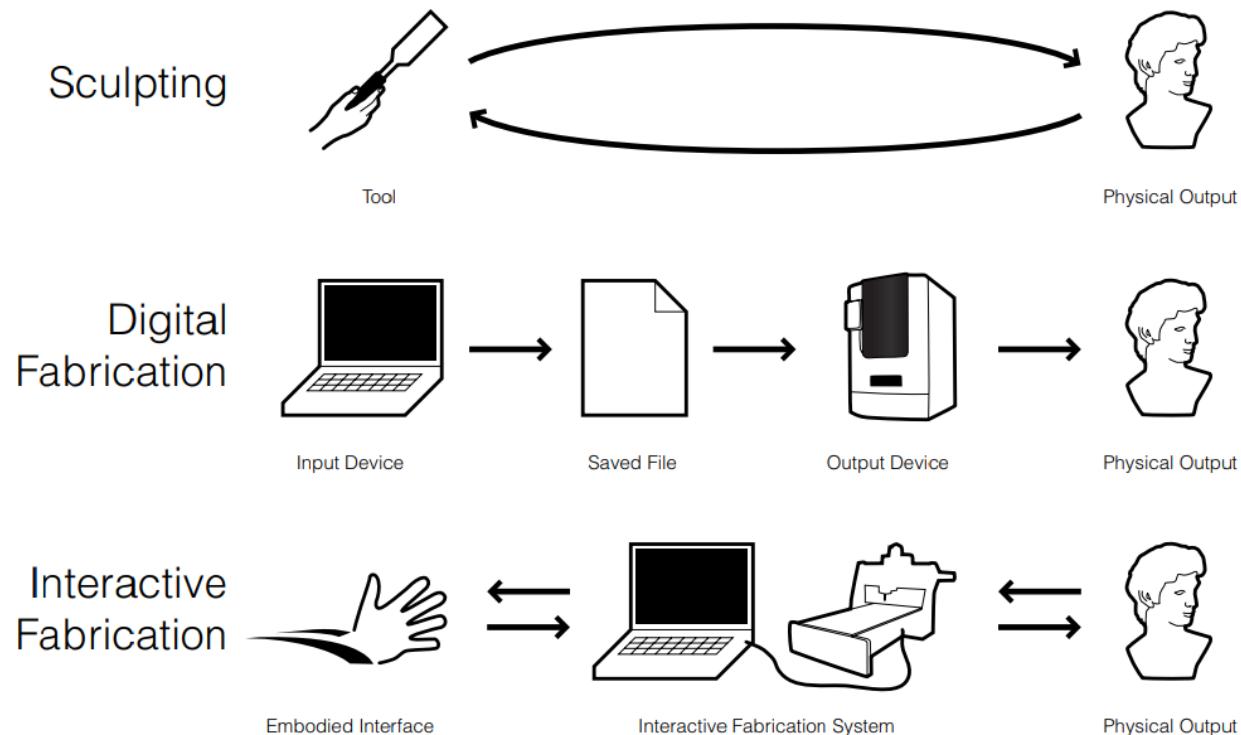
Ahn *et al.* invented a highly conductive silver ink that can be extruded at low temperatures. This led to the company Voxel8

FABRICATING INTERACTIVE DIGITAL-PHYSICAL OBJECTS

VOXEL8: 3D ELECTRONICS PRINTER

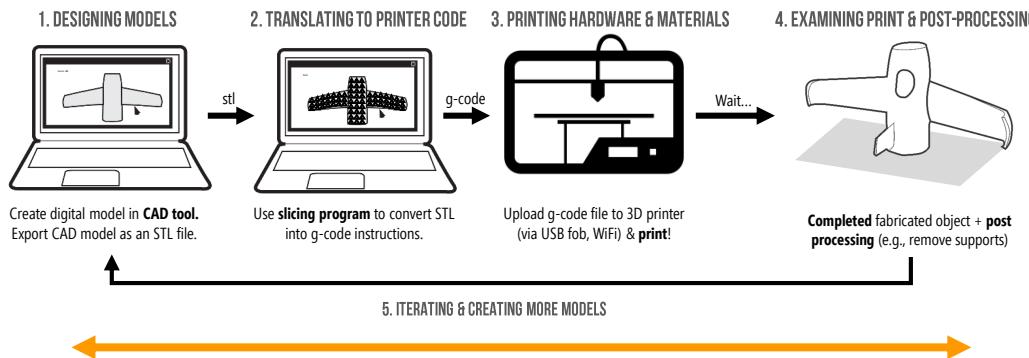


INTERACTIVELY MODELING & FABRICATING



Willis *et al.* argue that traditional fabrication design is too far removed from traditional craft. How to close gap between modeling and fabricating with computational tools?

INTERACTIVELY MODELING & FABRICATING



This research area **cuts across the full 3D-printing workflow** from custom design tools (or CAD plugins) to new printer hardware

How can we...

Enable users to interactively design and fabricate a model in (near) real-time?

INTERACTIVE FAB WITH AUGMENTED REALITY

CHI 2018 Paper
CHI 2018, April 21–26, 2018, Montréal, QC, Canada

RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer

Huaishu Peng¹, Jimmy Braga^{1*}, Cheng-Yao Wang¹, Kevin Guo¹, Joseph Kider⁴, Stefanie Mueller², Patrick Baudisch², François Guimbretière¹

Cornell University Ithaca, NY, USA
hp356,jeb482,cw776,kgs344,fvg31@cornell.edu

Hasso Plattner Institute Potsdam, Germany
patrick.baudisch@hpi.de

MIT CSAIL Cambridge, MA, USA
stefanie.mueller@mit.edu

Univ. of Central Florida Orlando, FL, USA
jkider@cs.ucf.edu

ABSTRACT
We present the Robotic Modeling Assistant (RoMA), an interactive fabrication system providing a fast, precise, hands-on and *in-situ* modeling experience. As a designer creates a new model using RoMA AR CAD editor, features are constructed concurrently by a 3D printing robotic arm sharing the same design view. The physically printed primitives can be used as a tangible reference for the designer as she adds new elements to her design. RoMA's proxemics-inspired handshake mechanism between the designer and the 3D printer allows the designer to quickly interact with the robot to access a printed area or to indicate that the robot can take full control of the model to finish printing. RoMA lets users integrate real-world constraints into a design rapidly, allowing them to create well-integrated new products or to extend existing objects. We conclude by presenting the strengths and limitations of our current design.

Author Keywords
3D printing; Augmented Reality; Interactive Fabrication; CAD; Rapid Prototyping; Physical Prototyping.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION
Interactive fabrication [43] entails a hands-on approach during the 3D modeling process to offer a reflective design experience. This concept has been developed with several approaches [4]. For example, Constructables [24] proposes a step-by-step laser cutting system to design 3D assemblies from 2D physical cutouts. D-Coil [28] allows the user to create a 3D digital model by directly handcutting its physical components. On-the-Fly Print [27] combines CAD digital modeling with direct low-fidelity physical rendering, while ReForm [41] combines hand modeling with digital carving of clay to create a 3D model. Each system has a different set of trade-offs. For example, the D-Coil process mirrors the hands-on approach of clay-carving, but forces the user to constantly switch between the physical and digital. ReFly prints produce low-fidelity models incrementally, but relies on an on-screen modeling process. Even with a model in-hand, it is not always easy to transfer design insight from the real-world back to a CAD model on the computer.

* To whom correspondence should be addressed.
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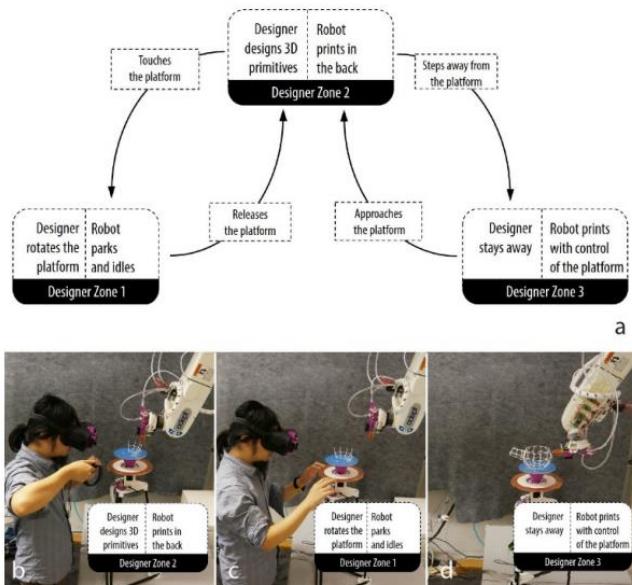
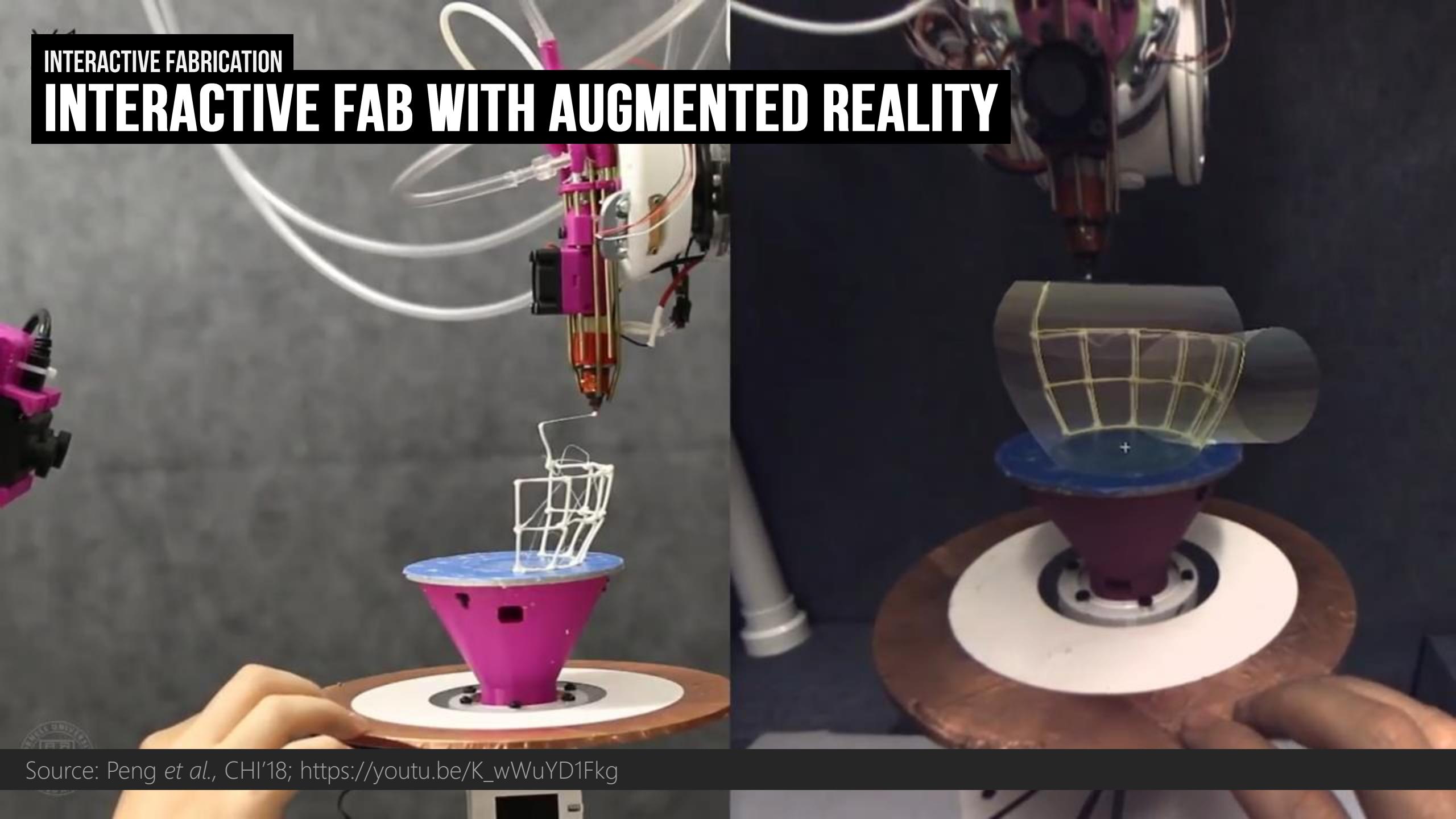


Figure 3. a) Proxemics interaction state machine diagram. Based on different designer zones, the designer can switch among activities such as digital modeling, rotating platform, and complete design; the robot will switch between printing and idle correspondingly. **b, c, d)** Interaction based on different proximity.

Presents a new interactive fabrication system using augmented reality and a robotic 3D printer

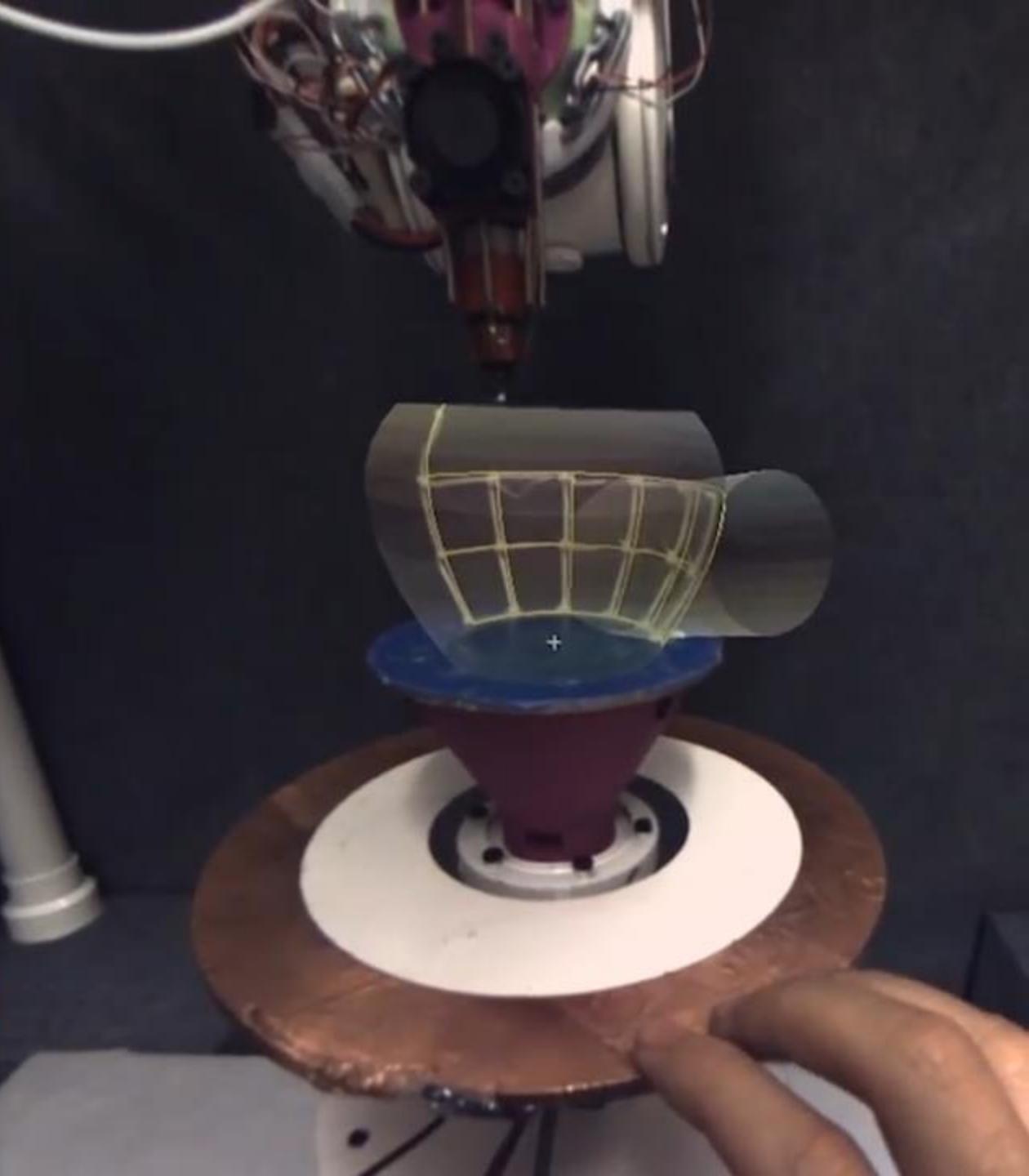
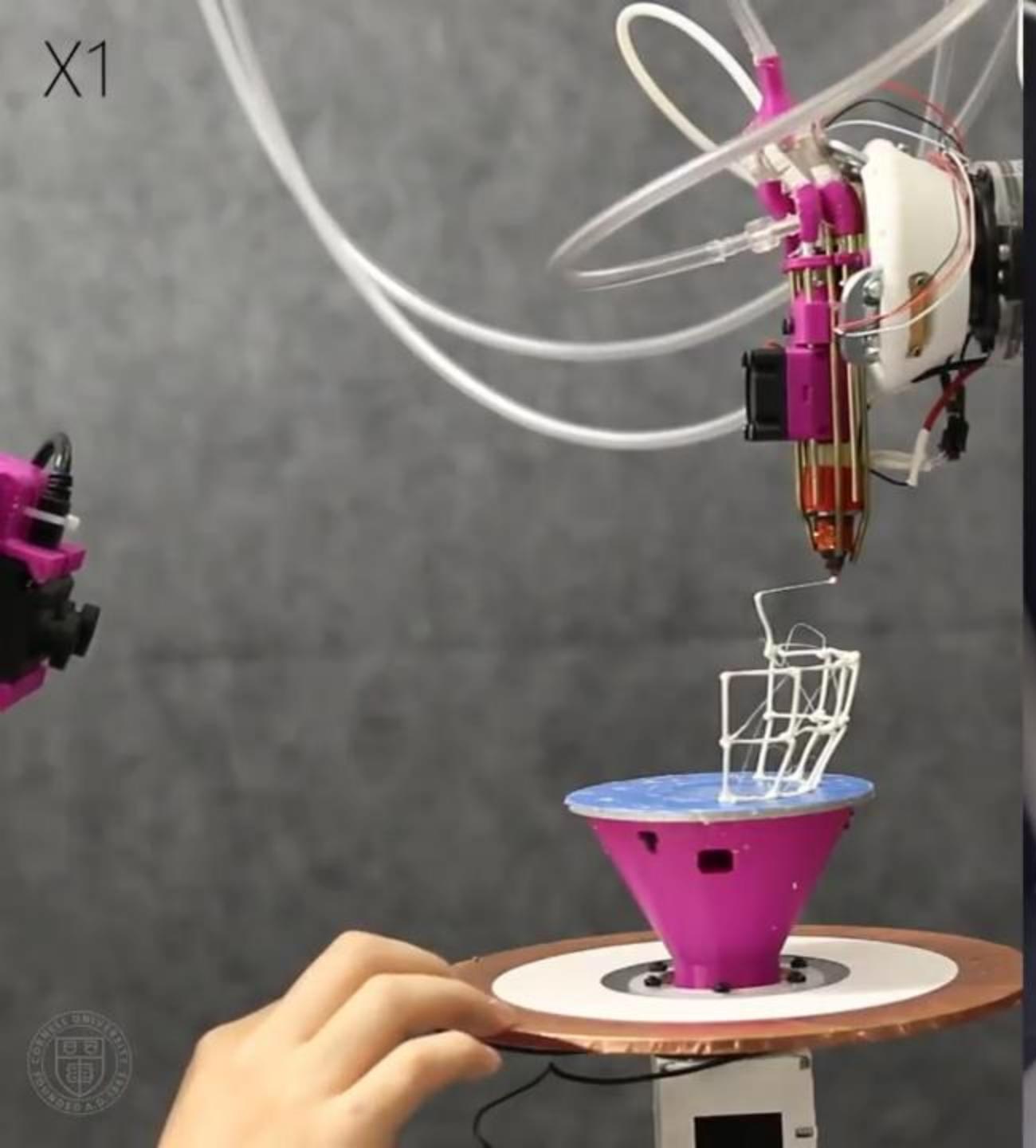
INTERACTIVE FABRICATION

INTERACTIVE FAB WITH AUGMENTED REALITY



Source: Peng *et al.*, CHI'18; https://youtu.be/K_wWuYD1Fkg

X1



HYBRID COMPUTER-MANUAL CONTROLLED MILLING

Session: Fabrication

CHI 2013: Changing Perspectives, Paris, France

FreeD – A Freehand Digital Sculpting Tool

Amit Zoran
Responsive Environments Group
MIT Media Lab
amitz@media.mit.edu

Joseph A. Paradiso
Responsive Environments Group
MIT Media Lab
joep@media.mit.edu

ABSTRACT

In this paper, we present an approach to combining digital fabrication and manual control of raw material. Engaging in an intimate fabrication process and enjoying the experience of shaping raw material are inherent values of traditional craft. As a result of this engagement, handcrafted products are unique and carry personal narratives [10]. Our research interest lies in the cross-section between digital fabrication and the study of the craft experience. We want to enable designers to engage with their physical material, not only the CAD model. We hope to encourage the exploration of an intimate digital fabrication approach, introducing craft qualities into the digital domain. Our contribution is a system merging qualities of both traditions: manufacturing fabrication risks and the experience of digital control of automation while allowing authentic engagement with raw material to achieve unique results.

Author Keywords
Computer-Aided Design (CAD); Craft; Digital Fabrication; Carving; Milling.

ACM Classification Keywords
H.5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION
Over the last several years, digital fabrication technologies have used many disciplines [4]. Today's designers can easily create, download, or modify a Computer-Aided Design (CAD) model of their desired object, and fabricate it directly using a digital process. In developing new manufacturing techniques, users seek to make the process as accessible, reducing access to as few barriers as possible, and separating design from fabrication. Ease of use, accessibility, proliferation and efficacy grow as technology matures. However, qualities such as creative engagement in the experience itself are lost. The nature of interaction with the fabricated artifact is rarely the focus of new developments.

While the process of engineering minimizes risks, seeks efficiency, and enables automation and repetition, craft is

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about involvement and engagement, uniqueness of the final product, and the experience of the process. Engaging in an intimate fabrication process and enjoying the experience of shaping raw material are inherent values of traditional craft. As a result of this engagement, handcrafted products are unique and carry personal narratives [10].

Our research interest lies in the cross-section between digital fabrication and the study of the craft experience. We want to enable designers to engage with their physical material, not only the CAD model. We hope to encourage the exploration of an intimate digital fabrication approach, introducing craft qualities into the digital domain. Our contribution is a system merging qualities of both traditions: manufacturing fabrication risks and the experience of digital control of automation while allowing authentic engagement with raw material to achieve unique results.

The *FreeD* is a freehand digitally controlled milling device (Figure 1). With the *FreeD* we harness CAD abilities in 3D design while keeping the user involved in the milling process. A computer monitors this 3D location-aware tool while presenting the user with gestural feedback. The computer intervenes only when the milling bit approaches the 3D model. In such a case, it will either slow down the spindle, or draw back the shaft; the rest of the time it allows the user to freely shape the work. Our hope is to substantiate the importance of engaging in a discipline that posits a new hybrid territory for investigation and discovery – a territory of artifacts produced by both machine and man.

Figure 1: (A) The *FreeD* and (B-C) the process of making a bowl from polyethylene foam.

RELATED WORK
There is a rich history of HCI researchers exploring the domain of creativity using motion tracking and gestural inputs. Several projects studied the 2D creative domain of painting and sketching [1, 3, 5], and others enable 3D crea-

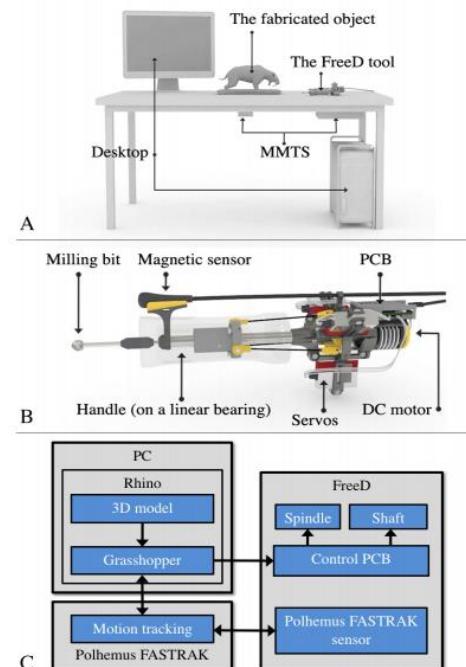


Figure 1: (A) The FreeD's environment, (B) the FreeD design, and (C) the system's data flow.

Presents a new hybrid computer-manual controlled milling approach

Computer monitors user's motion and slows down spindle or retracts it when milling bit risks object integrity. Uses pre-created CAD file for "ground truth."

INTERACTIVE FABRICATION

HANDHELD DIGITAL MILLING WITH COMPUTER CONTROL

The FreeD

A Handheld Digital Milling
Device for Craft & Fabrication

Amit Zoran & Joe Paradiso
Responsive Environment Group

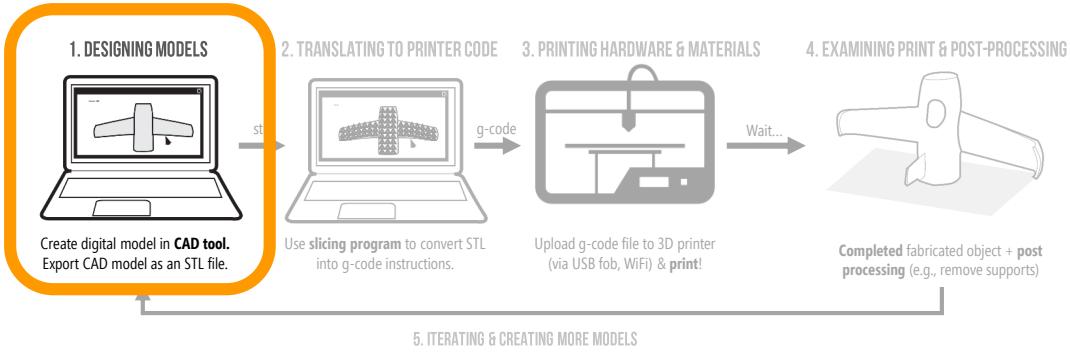


The FreeD

A Handheld Digital Milling
Device for Craft & Fabrication

Amit Zoran & Joe Paradiso
Responsive Environment Group





How can we...
Transform the experience of
designing CAD models?

RAPIDLY SKETCHING 3D MODELS IN 3D

Spatial Sketch: Bridging Between Movement & Fabrication

Karl D.D. Willis^{1,2} Juncong Lin² Jiajia Mitani² Takeo Igarashi²
¹Carnegie Mellon University ²JST, ERATO, Frontier Koishikawa Bldg., 7F 1-28-1,
5000 Forbes Avenue, Pittsburgh, PA, USA Koishikawa, Bunkyo-ku, Tokyo, Japan
karl@darcv.co.nz {justin, jmitani}@designinterface.jp takeo@acm.org

ABSTRACT
Spatial Sketch is a three-dimensional (3D) sketch application that bridges between physical movement and the fabrication of objects in the real world via cut planar materials. This paper explores the rationale and details behind the development of the *Spatial Sketch* application, and presents our observations from user testing and a hands-on lamp shade design workshop. Finally we reflect upon the relevance of embodied forms of human computer interaction for use in digital fabrication.

Author Keywords
Sketching, drawing, creativity, design, 3D interfaces, fabrication, embodied interaction, rapid prototyping.

ACM Classification Keywords
HS.3.m. Information interfaces and presentation (e.g., HCI): User Interfaces; Input devices and strategies, Theory and methods.

General Terms
Algorithms, Design, Experimentation, Human Factors

INTRODUCTION
The broader goal of our research is to develop computational systems that cultivate the creativity of a wide audience of people and support self-expression through the fabrication of real-world entities. While graphical user interfaces (GUIs) have been the dominant style for systems focused on everyday creativity and self-expression, non-GUI interfaces have proven to be a powerful tool to engage a wide range of people with the possibilities offered by computation. In particular, *embodied interfaces* combine physical experience [4], allows even those unfamiliar with current interface paradigms to interact with computational systems. Such

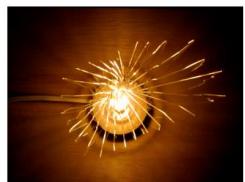


Figure 1. A lamp shade designed and fabricated from physical movement using the *Spatial Sketch* application.

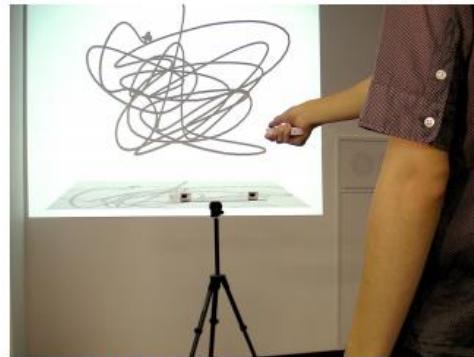


Figure 2. Sketching with the *Spatial Sketch* application.

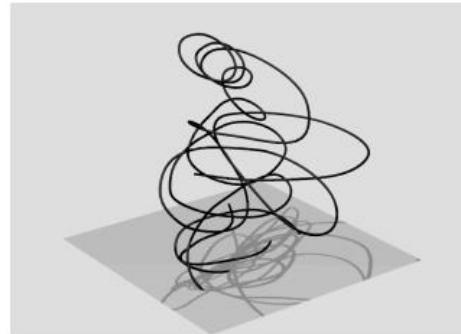


Figure 3. A sketch created using the *Spatial Sketch* 3D input system with line smoothing applied in real-time.

Invites us to rethink approaches to CAD modeling.

Presents a 3D sketching tool that is controlled by arm movement.

Validates approach via a design workshop with children

NEW CAD APPROACHES

RAPIDLY SKETCHING 3D MODELS IN 3D

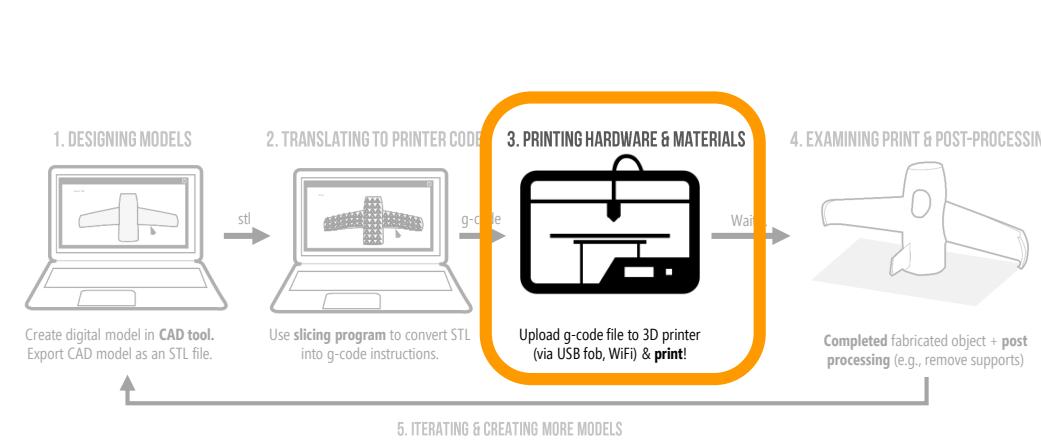
Spatial Sketch

The background of the image is a dense, abstract pattern of black and white shapes. These shapes are roughly triangular and rectangular, creating a complex, organic texture that resembles a stylized tree or perhaps a microscopic view of a cellular or crystalline structure. The overall effect is one of depth and organic complexity.

Spatial Sketch

INNOVATING FDM HARDWARE

HOW CAN WE IMPROVE FDM HARDWARE?



How can we...

Improve FDM hardware to enable new types of fabricated designs?

REVOMAKER: FDM USING A ROTATIONAL CUBOIDAL PLATFORM

RevoMaker: Enabling Multi-directional and Functionally-embedded 3D Printing using a Rotational Cuboidal Platform

Wei Gao¹, Yunbo Zhang¹, Diogo C. Nazzetta¹, Karthik Ramani¹, Raymond J. Cipra¹
¹School of Mechanical Engineering, Purdue University
West Lafayette, IN 47907
(gao51, ybzhang, dn, ramani, cipra)@purdue.edu

ABSTRACT
In recent years, 3D printing has gained significant attention from the maker community, academia, and industry to support low-cost and rapid prototyping of designs. Current printing extrusion process requires printing support material to support printed features such as overhangs. Furthermore, integrating functions such as sensing and actuation into these prints requires additional steps and processes to create functional enclosures, where design functionality cannot be easily embedded into the print. All of these factors result in relatively high design iteration times.

We present “RevoMaker”, a self-contained 3D printer that creates direct out-of-the-primer functional prototypes, using less build material and with substantially less reliance on support structures. By modifying the standard FDM printer with a revolved cuboidal platform and printing partitioned geometries around cuboidal frames to achieve a multi-directional additive prototyping process to reduce the print and support consumption. Our novel frame-based framework sides various orientations for the cuboidal base. The mechanical, electronic, and sensory components are pre-assembled in the flatbed; laser-cut facets are inserted inside the cuboid which demonstrate RevoMaker’s diverse printing variety of customized and fully-functional product prototypes, such as computer mice and toys, thus illustrating the new affordances of 3D printing for functional product design.

Author Keywords
Multi-directional 3D printing; functional product design.

ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation] : User Interfaces.
“Wei Gao and Yunbo Zhang contributed equally to this paper.”

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https://doi.org/10.1145/2807421.2807476

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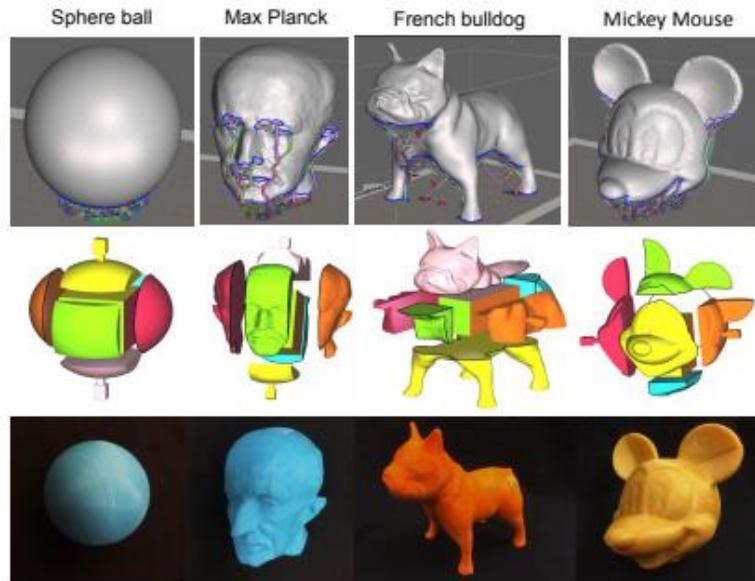


Figure 10. first row: visualization of support generation for a sphere ball, Max Planck, French bulldog and Mickey Mouse head using existing FDM printing process in Ultimaker2 (the model is oriented where less support structures are created. second row: partitioned results of each model. third row: prototypical results of each model

Modifies existing FDM printer to use rotational cuboidal platform

Benefits include less build material, less reliance on support material, and an easy method for embedding electronics

REVOMAKER: FDM USING A ROTATIONAL CUBOIDAL PLATFORM

Table 1. Comparison of time and total material reduction using RevoMaker and Ultimaker 2.

Models	RevoMaker		Ultimaker 2				time reduction	total material reduction		
	total time (hh:mm)	build volume (cm^3)	time (hh:mm)		build volume (cm^3)					
			t_{min}	t_{max}	V_{min} ($V_{support}$)	V_{max} ($V_{support}$)				
Sphere	4:03	61.7	4:58	4:58	77.9 (0.3)	77.9 (0.3)	18.4%	20.8%		
Max Planck	6:11	114.6	8:13	9:16	142.6 (7.4)	163.8 (28.6)	23.5%	19.6%		
Bulldog	7:36	133.8	10:52	12:43	177.3 (26.7)	215.9 (65.3)	20.8%	24.5%		
Mickey	6:15	112.2	8:22	15:01	138.4 (6.4)	257.2 (125.2)	25.3%	18.9%		
Star	9:06	165.5	11:25	13:32	200.6 (12.6)	231.9 (43.9)	20.3%	17.5%		
PC Mouse	2:55	48.4	4:38	6:44	76.7 (10.9)	111.3 (45.6)	37.0%	36.8%		
Bulbasaur	5:24	93.7	6:37	7:17	109.7 (1.7)	121.6 (13.6)	18.39%	14.6%		

*By placing a model in different orientations, t_{min} and t_{max} are the minimum and maximum time duration using Ultimaker 2; V_{min} and V_{max} are the minimum and maximum consumption of overall material (build + support), $V_{support}$ is only the consumption of support material. Using RevoMaker, the time statistics of Cuboidization for each selected model (top down), included in the total time, are 30s, 2min 33s, 6min 45s, 5min 03s, 1min 10s, 1min 02 s, 4 min 17s, respectively.

INNOVATING FDM HARDWARE

REVOMAKER: FDM USING A ROTATIONAL CUBOIDAL PLATFORM

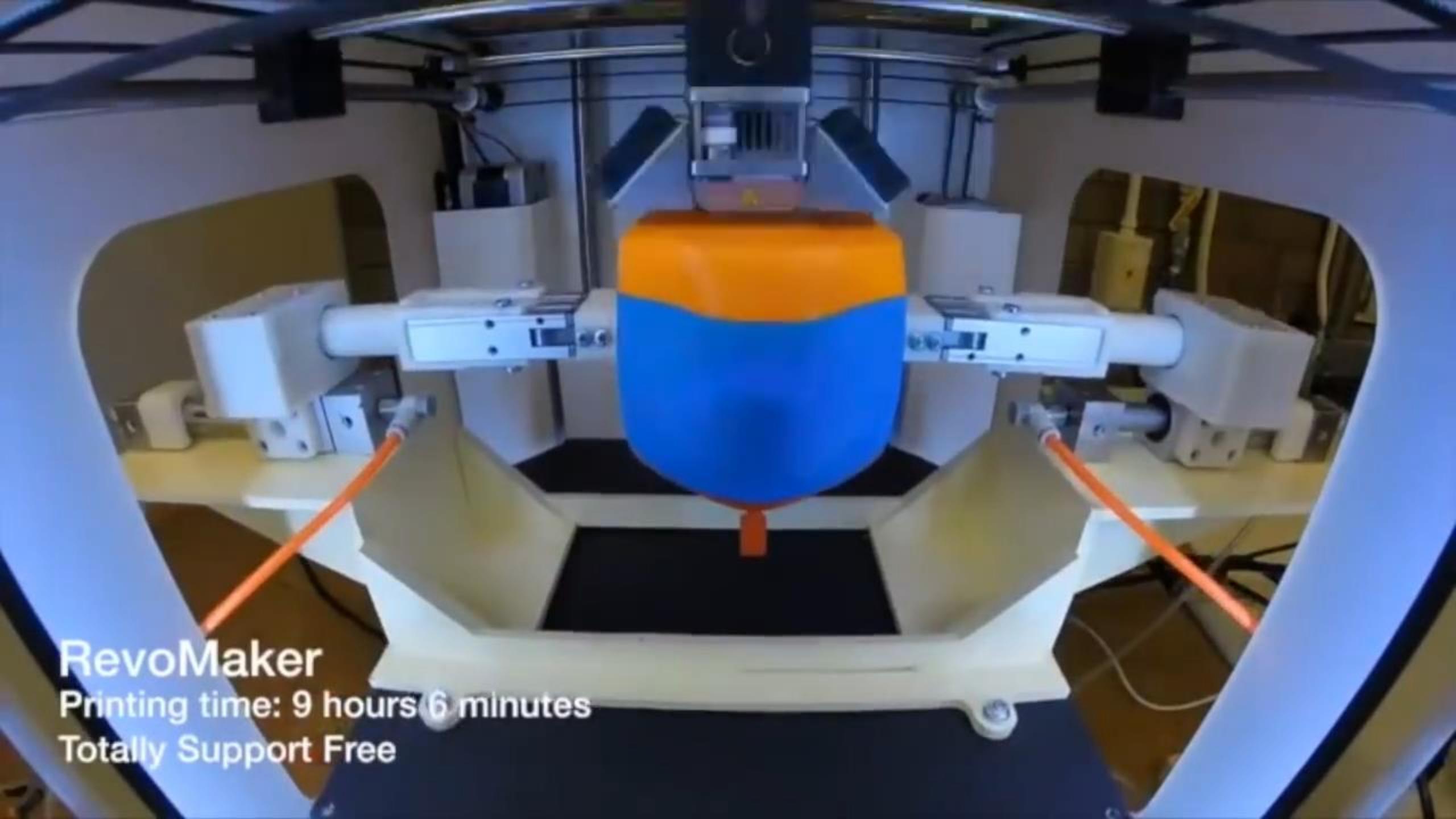


RevoMaker

Printing time: 9 hours 6 minutes

Totally Support Free

Source: Gao et al., UIST'15; <https://youtu.be/y2xlZL-9r-s>

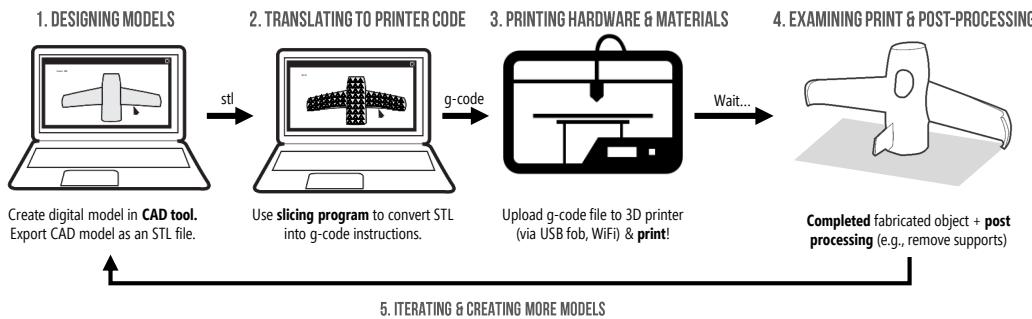


RevoMaker

Printing time: 9 hours 6 minutes
Totally Support Free

IMPROVING ROBUSTNESS

HOW TO IMPROVE ROBUSTNESS



How can we...

Enable designers to improve the robustness of their designs and eliminate support material?

STOCHASTIC STRUCTURAL ANALYSIS

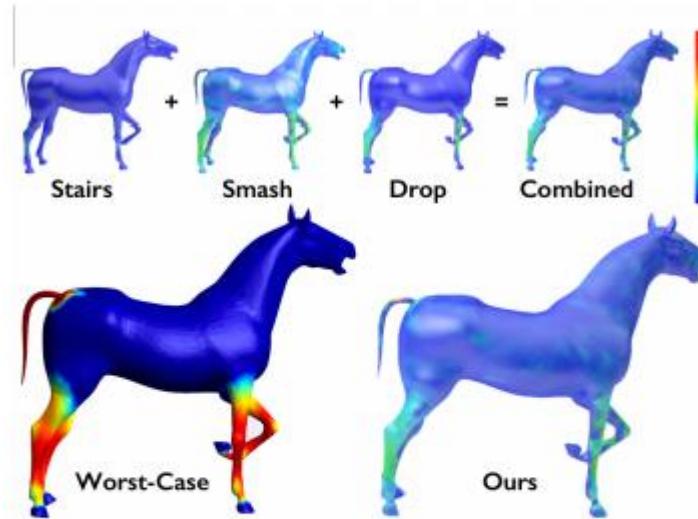
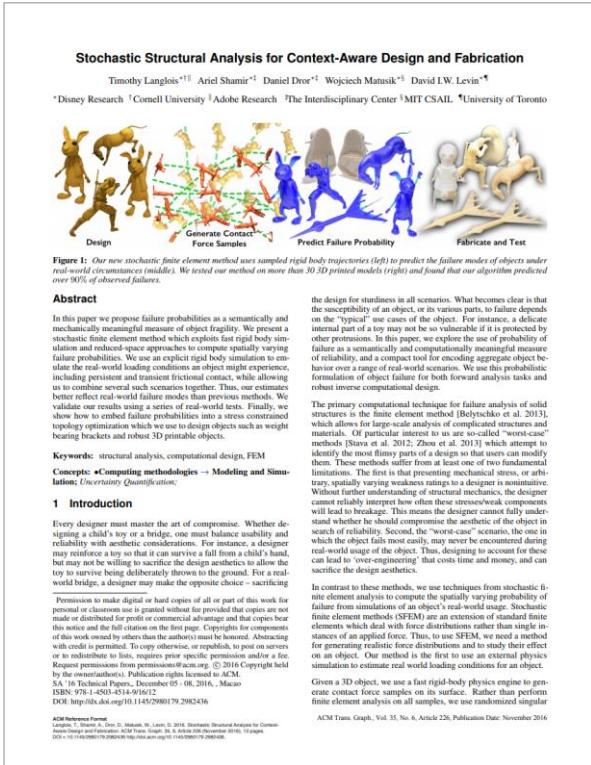


Figure 7: Top: Our method supports seamlessly combining samples from multiple scenarios to provide an aggregate analysis. Bottom: We compare our combined results to the worst-case analysis for the same pose. Worst-case both fails to predict the non-fragile legs in the stairs and drop cases as well as misses the fragile body and mouth regions in the smash and combined cases.

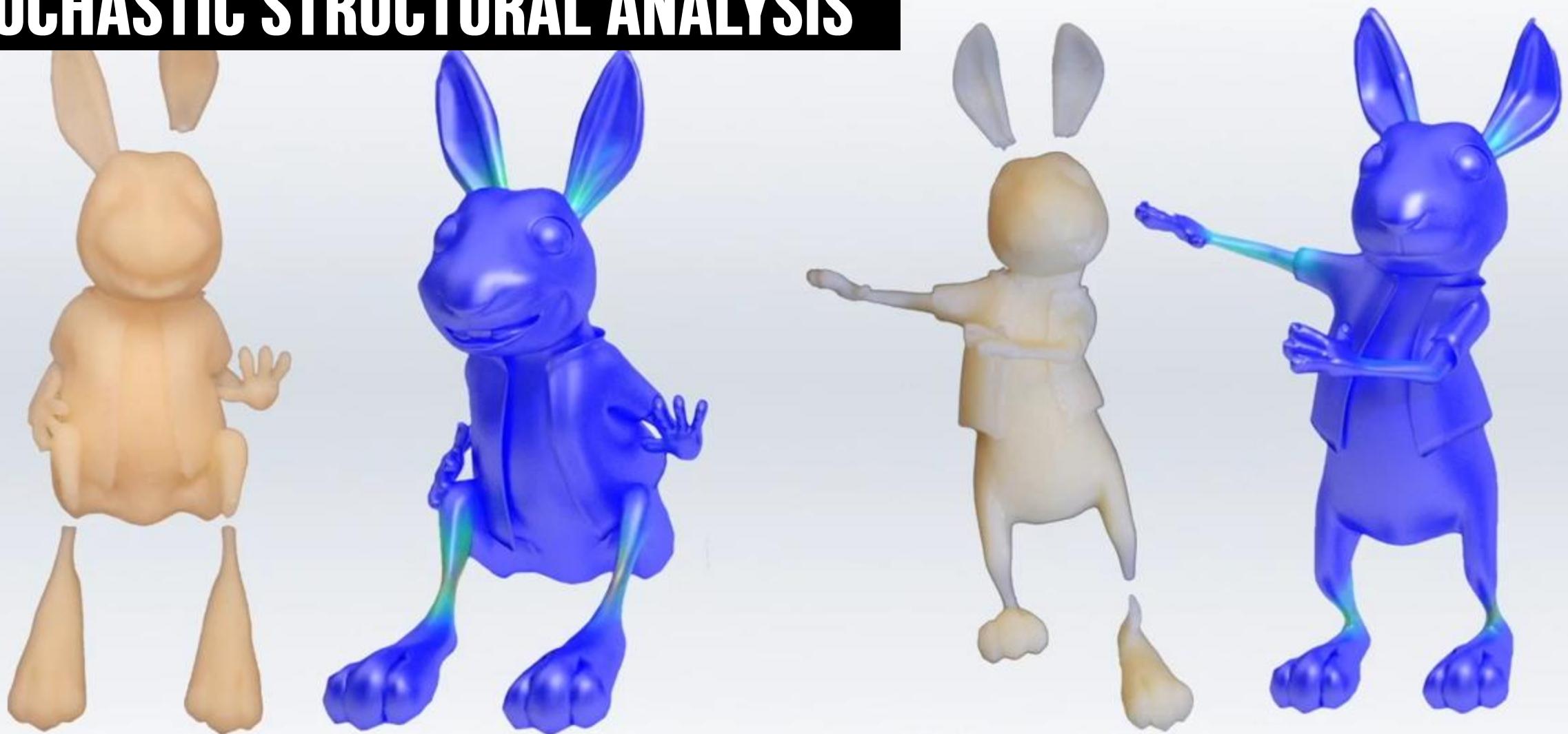
Improves upon traditional finite element analyses with a stochastic model

Identifies more accurate failure probabilities than status quo

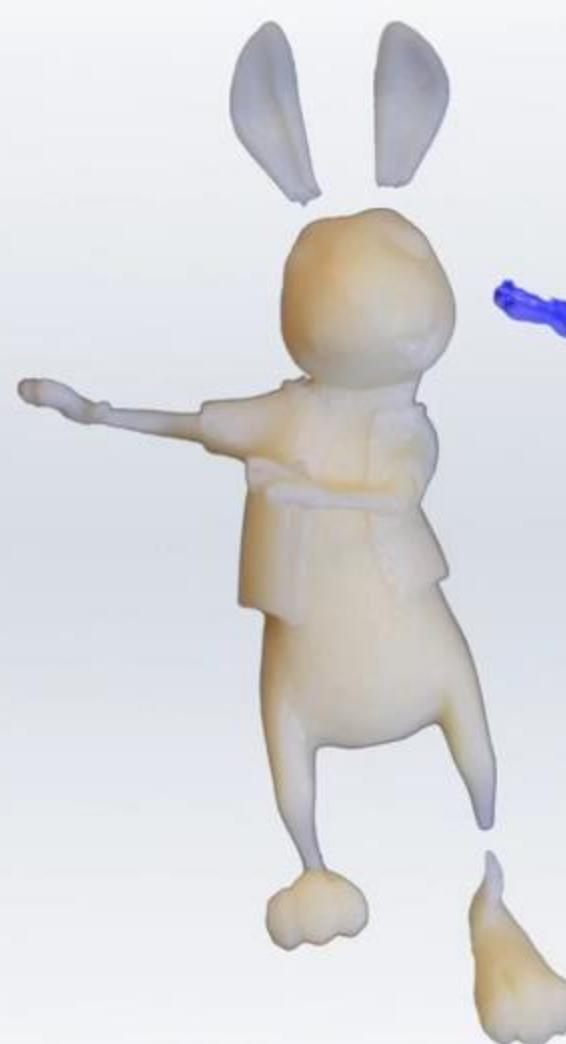
Validated via real-world drop experiments (stairs, smash, drop)

IMPROVING ROBUSTNESS

STOCHASTIC STRUCTURAL ANALYSIS

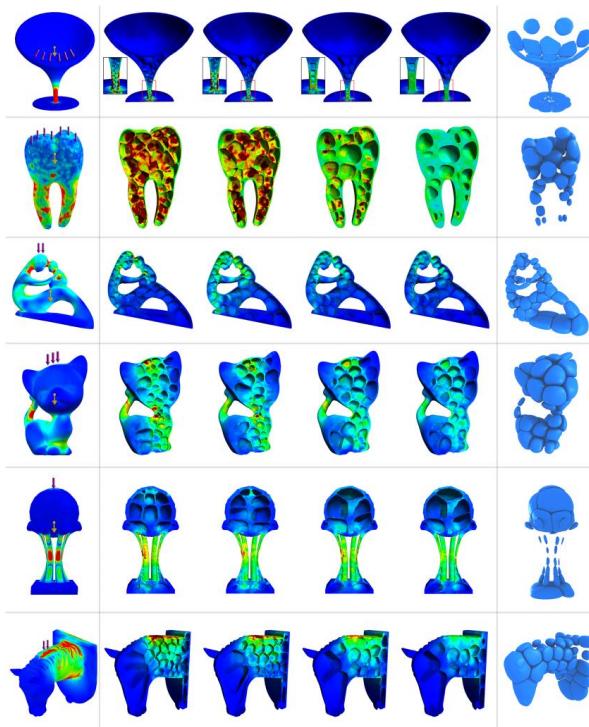
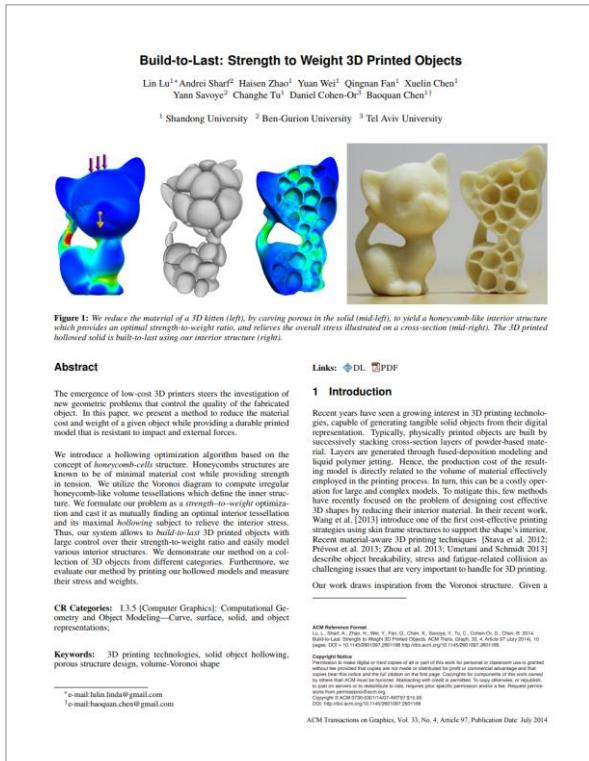


Source: Langlois *et al.*, 2016; <https://www.youtube.com/watch?v=xTJ7Ha6Q1Tw>



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OPTIMIZING INFILL TO REDUCE WEIGHT BUT MAINTAIN DURABILITY



Contributes a new infill algorithm to reduce the material cost and weight of a given object while maintaining or improving durability

Validates method empirically using mechanical stress testing

IMPROVING ROBUSTNESS

OPTIMIZING INFILL TO REDUCE WEIGHT BUT MAINTAIN DURABILITY





IMPROVING ROBUSTNESS

MODIFYING INFILL & SHAPE TO IMPROVE OBJECT BALANCE

Make It Stand: Balancing Shapes for 3D Fabrication

Romain Prévost¹ Emily Whiting¹ Sylvain Lefebvre² Olga Sorkine-Hornung¹

¹ETH Zurich ²INRIA

Figure 1: Our algorithm iterates between carving and deformation to reach the final, balanced result. (a) The original horse model does not stand on its hind legs and requires using the tail as a third support. (b) Our approach deforms the horse to make it stand on a single hind leg. (c,d) The user scales up the head of the T-Rex. Our optimizer succeeds in finding the delicate balance of a massive head and body on a tiny base of support. It deforms and carves the model (yellow region visible by transparency) to precisely position the center of mass.

Abstract

Imbalance suggests a feeling of dizziness and movement in static objects. It is therefore not surprising that many 3D models stand in impossibly balanced configurations. As long as the models remain in a computer they are of course safe, the laws of physics do not apply. However, once they leave the screen, these impossible, printed models topple instead of standing as initially intended. We propose to assist users in producing novel, properly balanced designs by interactively deforming an existing model. We formalize the problem of achieving mechanical equilibrium and stability by modifying the *volume* of the object, while preserving its surface details. This takes place during interactive editing: the user cooperates with the system to define a target pose, and the system iterates over our method on a variety of models. With our technique, users can produce fabricated objects that stand in one or more surprising poses without requiring glue or heavy pedestals.

CR Categories: I.3.7 [Computer Graphics]: Computational Geometry and Object Modeling—Geometric algorithms, languages, and systems; Physically based modeling

Keywords: Static equilibrium, structural stability, 3D printing, optimization, interactive shape modeling

Links: [DL](#) [PDF](#) [Web](#) [VIDEO](#)

ACM Reference Format:
Prévost, R., Whiting, E., Lefebvre, S., and Sorkine-Hornung, O. 2013. Make It Stand: Balancing Shapes for 3D Fabrication. In *ACM SIGGRAPH Asia 2013 Papers*, 1–10. DOI: <https://doi.org/10.1145/2501388.2501397>.

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<https://doi.org/10.1145/2501388.2501397>

ACM Transactions on Graphics, Vol. 32, No. 4, Article #1. Publication Date: July 2013



Figure 7: (Left) Original model. (Middle) The user wishes to balance the model in an upside-down pose. She selects a number of handles for the optimizer. (Right) The carved, deformed model is balanced and stands on its head after printing.



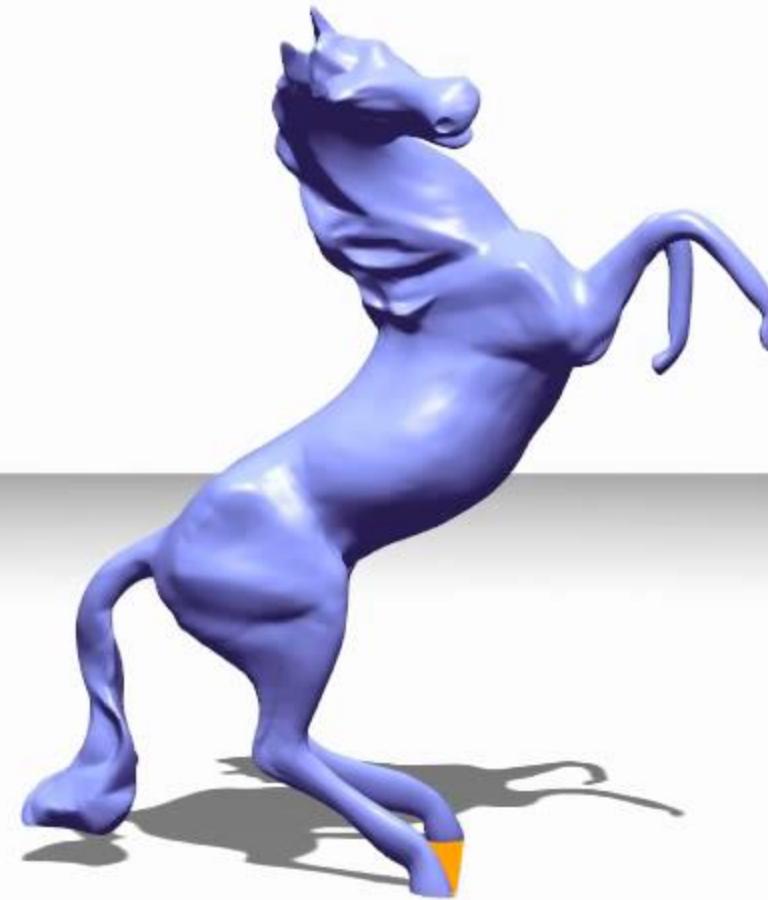
Figure 8: Armadillo model with different starting poses. (Left) Unstable input. (Middle) Balanced result. (Right) Printed model.

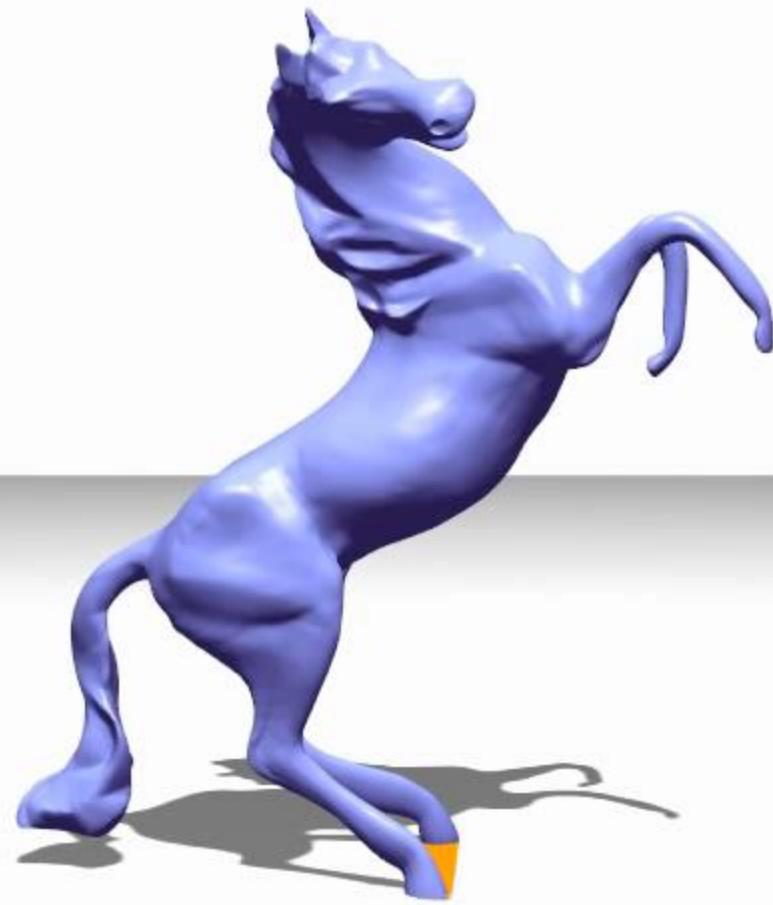
Contributes a new algorithm for balance optimization using infill operations

Validates approach via demonstration on a variety of models.

IMPROVING ROBUSTNESS

MODIFYING INFILL & SHAPE TO IMPROVE OBJECT BALANCE





PATCHING 3D-PRINTED OBJECTS

Patching Physical Objects

Alexander Teibrich¹, Stefanie Mueller¹, François Guimbretière^{1,2}, Robert Kovacs¹, Stefan Neubert¹, Patrick Baudisch¹

¹Hasso Plattner Institute
Potsdam, Germany
firstname.lastname@hpi.uni-potsdam.de

²Cornell University, Information Science
Ithaca, NY 14850, USA
francois@cs.cornell.edu

ABSTRACT
Personal fabrication is currently a one-way process: once an object has been fabricated with a 3D printer, it cannot be changed anymore. Any change requires printing a new version from scratch. The problem is that this approach ignores the nature of design *iteration*, i.e. that in subsequent iterations, large parts of an object stay the same and only small pieces change. This makes fabricating from scratch feel unnecessary and wasteful.

In this paper, we propose a different approach: instead of re-printing the entire object from scratch, we suggest patching the existing object to reflect the next design iteration. We built a system on top of a 3D printer that can accomplish this. Users scan an object with the 3D printer, then load both the original and the modified 3D model into our software, which in turn calculates how to patch the object. After identifying which parts to remove and what to add, our system locates the existing object in the printer using a depth camera. By first scanning the object, orienting the orientation, a mill first removes the outdated geometry, then a print head prints the new geometry in place.

Since only a fraction of the entire object is refabricated, our approach reduces material consumption and plastic waste (for our example objects by 82% and 93% respectively).

Author Keywords: rapid prototyping; 3D printing; sustainability.

ACM Classification Keywords: H.5.2 [Information interfaces and presentation]: User interfaces.

General Terms: Design, Human Factors.

INTRODUCTION

Personal fabrication machines, such as 3D printers, are on the verge of becoming a mass market [10]. With more people owning a 3D printer, more and more objects will be printed in the future. Many researchers envision a future in which even individualized users will create their own designs via a design-fabricate-test-redesign cycle [4].

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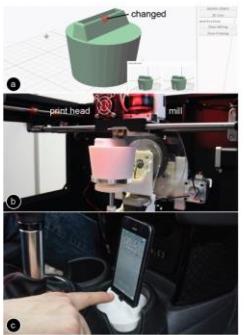


Figure 1: To minimize material consumption and to reduce the amount of waste, we propose *patching* the existing object rather than reprinting it from scratch. (a) First, our software calculates which part changed, then (b) a mill removes outdated geometry, followed by a print head that prints the new geometry.

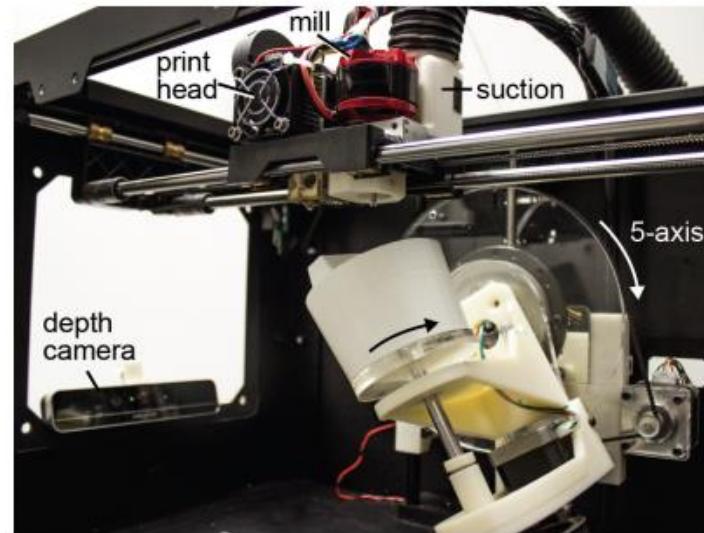


Figure 2: Hardware for patching physical objects.

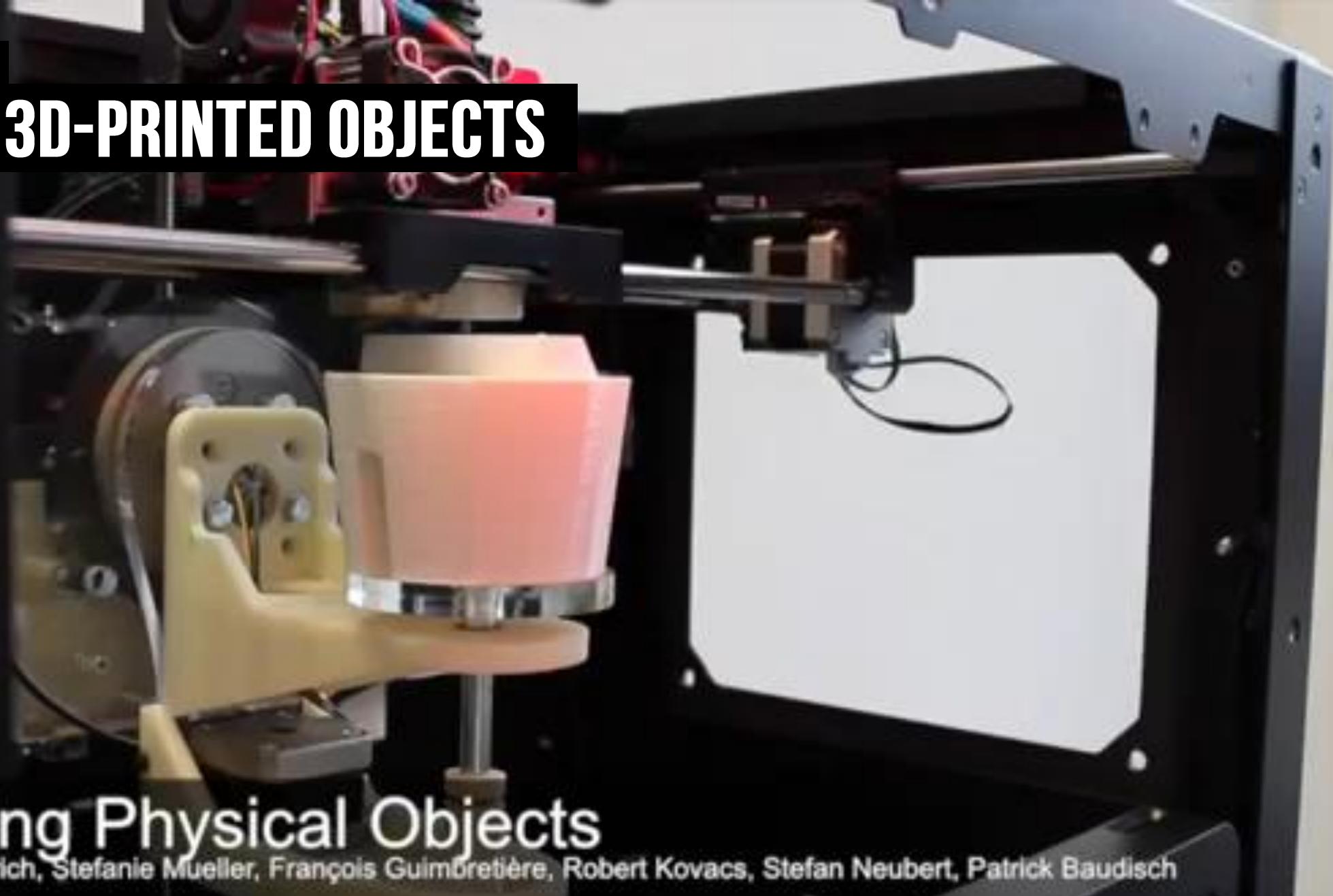
Contributes a new workflow for iterating on 3D-printed objects.

Custom fabrication machine can scan and mill previously printed parts to improve/repair

Reduces material consumption and waste

SUPPORTING ITERATION

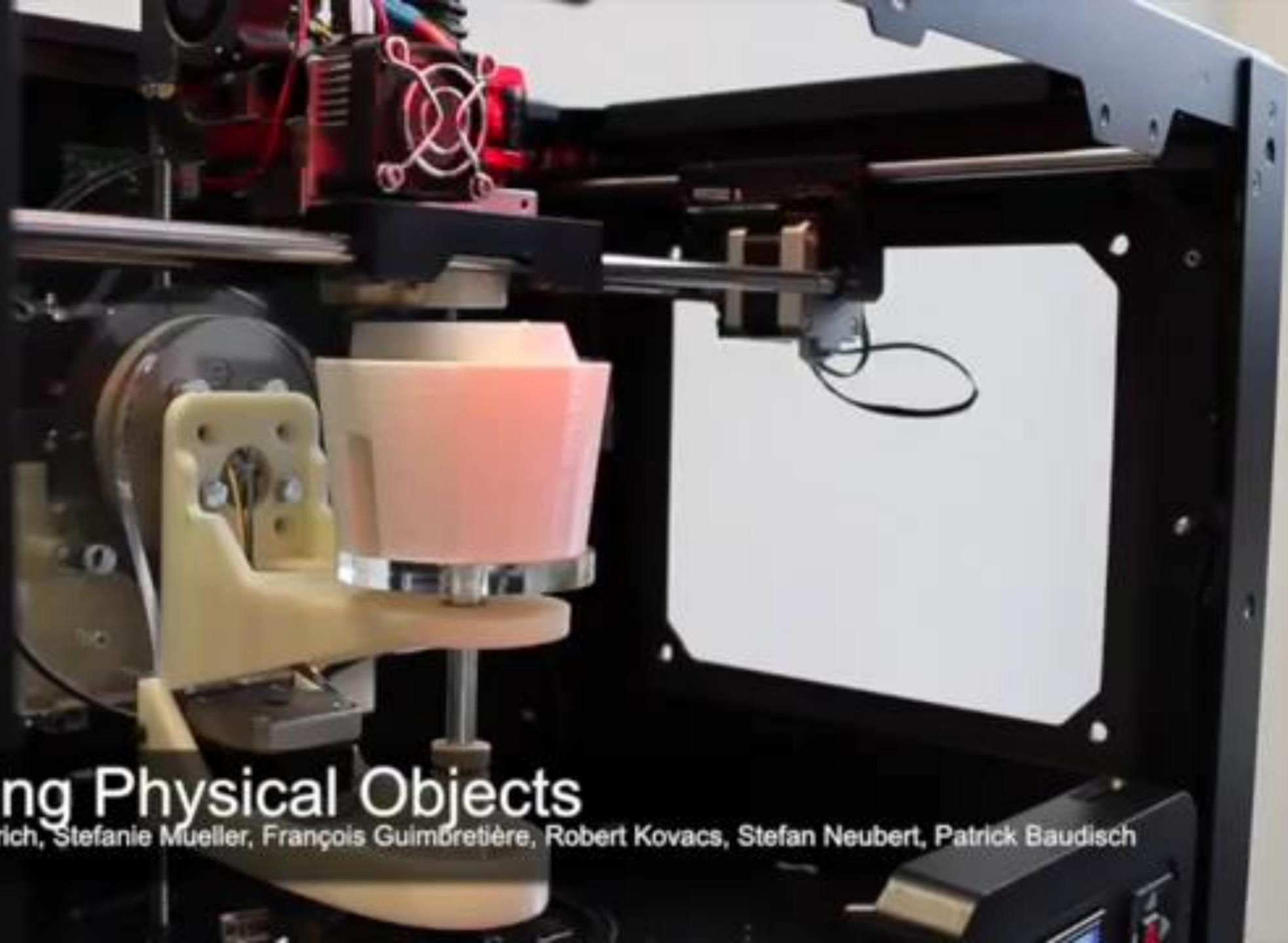
PATCHING 3D-PRINTED OBJECTS



Patching Physical Objects

Alexander Teibrich, Stefanie Mueller, François Guimbretière, Robert Kovacs, Stefan Neubert, Patrick Baudisch

Source: Teibrich *et al.*, UIST'15; <https://youtu.be/dO6FaZ38vF8>



Patching Physical Objects

Alexander Telbrich, Stefanie Mueller, François Guimbretière, Robert Kovacs, Stefan Neubert, Patrick Baudisch

ENCORE: 3D-PRINTED AUGMENTATION OF OBJECTS

Encore: 3D Printed Augmentation of Everyday Objects with Printed-Over, Affixed and Interlocked Attachments

Xiang 'Anthony' Chen¹, Stelian Coros², Jennifer Mankoff¹, Scott E. Hudson¹

¹HCI Institute, Robotics Institute

Carnegie Mellon University

{xiangchen, scoros}@cmu.edu, {jmankoff, scott.hudson}@cs.cmu.edu



Figure 1. Examples of how existing objects can be augmented using our techniques: a) turning a battery into a LED torch; b) making a magnet from a Teddy bear; c) adding a stand to a glue gun and d) attaching a name tag to a pair of scissors.

ABSTRACT

One powerful aspect of 3D printing is its ability to extend, repair, or make generally modify everyday objects. However, nearly all existing work implicitly assumes that whole objects are to be printed from scratch. Designing objects as extensions or enhancements of existing ones is a laborious process in most of today's 3D authoring tools. This paper presents a unified framework for printing to augment existing objects that covers a wide range of attachment options. We illustrate the framework through three exemplar attachment techniques – print-over, print-to-affix, and print-through, implemented in Encore, a design tool that includes a set of analysis metrics related to viability, durability, and cost that are intended for the user to explore design options and tradeoffs. Encore also generates 3D models for production, addressing issues such as support jigs and contact geometry between the attached part and the host object. Our validation studies show to illustrate the strengths and weaks of each technique. For example, we characterize how surface curvature and roughness affect print-over's strength compared to the conventional print-in-one-piece.

Author Keywords

Fabrication, 3D printing, attachments, analysis.

ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces.

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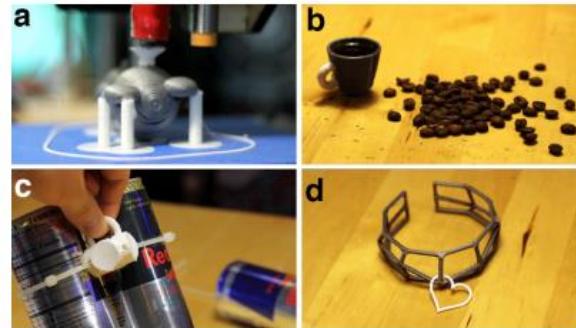


Figure 3. a) The magnet holder printed directly on a teddy bear that was scaffolded on support structures; b) a handle added to an espresso cup; c) strapping to make a reusable “4 pack” handle; and d) a bracelet printed through a heart-shaped charm.

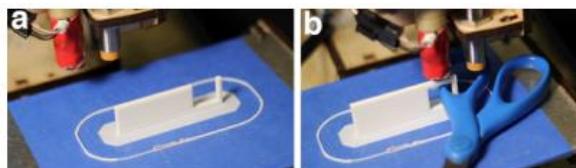


Figure 4. Example of a print-through process: the printer pauses at a point where the scissors can be dropped to interlock with the name tag, after which the print job resumes.

Contributes a new framework for 3D printing to augment existing objects

Distills three key attachment techniques: *print-over*, *print-to-affix*, and *print-through*

Provides a custom design tool

AUGMENTING EXISTING OBJECTS

ENCORE: 3D-PRINTED AUGMENTATION OF OBJECTS





Reprise: A Design Tool for Specifying, Generating, and Customizing 3D Printable Adaptations on Everyday Objects

Xiang ‘Anthony’ Chen[†], Jeeeun Kim[‡], Jennifer Mankoff[†], Tovi Grossman[§],
Stelian Coros[†], Scott E. Hudson[†]

[†]Carnegie Mellon University [‡]University of Colorado Boulder [§]Autodesk Research

[†]{xiangche, scoros, jmankoff, scott.hudson}@cs.cmu.edu [‡]jeeeun.kim@colorado.edu

[§]tovi.grossman@autodesk.com

ABSTRACT

Everyday tools and objects often need to be customized for an unplanned use or adapted for specific user, such as adding a bigger pull to a zipper or a larger grip for a pen. The advent of low-cost 3D printing offers the possibility to rapidly construct a wide range of such adaptations. However, while 3D printers are now affordable enough for even home use, the tools needed to design custom adaptations normally require skills that are beyond users with limited 3D modeling experience.

In this paper, we describe Reprise—a design tool for specifying, generating, customizing and fitting adaptations onto existing household objects. Reprise allows users to express at a high level what type of action is applied to an object. Based on this high level specification, Reprise automatically generates adaptations. Users can use simple sliders to customize the adaptations to better suit their particular needs and preferences, such as increasing the tightness for gripping, enhancing torque for rotation, or making a larger base for stability. Finally,

be out of reach for a child, thus it needs to be extended¹ (Figure 2a); it is hard to hold a drill bit straight while sharpening it, thus a guide comes in handy to keep it in place² (Figure 2b); painting a big surface with a spray-can could be fatiguing for the fingers, thus a mechanism can be used to turn it into a spray-gun³ (Figure 2c). These add-on components are called *adaptations*. Adaptations change the mechanical properties of existing objects to make them more accessible or to customize them for specific use cases.

The advent of low-cost 3D printing offers the possibility to rapidly construct a wide range of adaptations. However, designing or re-purposing adaptations is hard with general-purpose 3D modeling software, as it requires a certain level of expertise from users [7]. In general, 3D modeling tools do not take into account how an object is used, what adaptation strategy is available, or how to rapidly generate the corresponding geometry or further customize it.



A PICTURE IS WORTH A THOUSAND WORDS...
BUT WHAT IF YOU COULDN'T SEE IT?

We are building the research and technology to create tactile pictures for children.

We want to make the world a tangible and accessible place for every child.

COMPUTER VISION + 3D-PRINTING -> TACTILE BOOKS



Facade: Auto-generating Tactile Interfaces to Appliances

Anhong Guo¹, Jeeeun Kim², Xiang ‘Anthony’ Chen¹, Tom Yeh², Scott E. Hudson¹,
Jennifer Mankoff¹, Jeffrey P. Bigham¹

¹ Human-Computer Interaction Institute, Carnegie Mellon University, Pittsburgh, PA, USA

² Department of Computer Science, University of Colorado Boulder, Boulder, CO, USA

{anhongg, xiangche, scott.hudson, jmankoff, jbigham}@cs.cmu.edu,
{jeeeon.kim, tom.yeh}@colorado.edu



Figure 1. Facade is a crowdsourced fabrication pipeline that enables blind people to make flat physical interfaces accessible by independently producing a 3D-printed overlay of tactile buttons. From left to right, we demonstrate example applications including microwave, refrigerator door, copier, and another microwave. Insets shows close views of individual embossed buttons.

ABSTRACT

Common appliances have shifted toward flat interface panels, making them inaccessible to blind people. Although blind people can label appliances with Braille stickers, doing

Author Keywords

Non-visual interfaces; visually impaired; blind; accessibility; crowdsourcing; fabrication; 3D printing; computer vision.

AUGMENTING EXISTING OBJECTS

FAÇADE: AUTO-GENERATING TACTILE INTERFACES



**Blind Participant 3
Task: Time Cook. 1'30"**

Blind Participant 3
Task: Time Cook, 1'30"