3D PRINTING RESEARCH IN UBICOMP & BEYOND

CSE 590 Ubiquitous Computing | Lecture 10 | May 24

Jon Froehlich • Liang He (TA)

DESIGN USE BUILD

MAKEABILITY LAB

PAUL G. ALLEN SCHOOL OF COMPUTER SCIENCE & ENGINEERING

UNIVERSITY of WASHINGTON

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

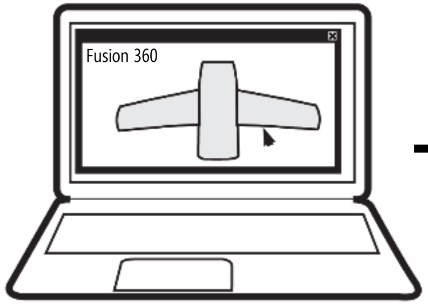
We will meet next Thurs, June 7 at 6:30PM (regular time)

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

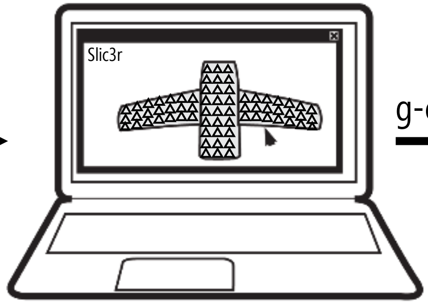
1. DESIGNING MODELS



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

stl →

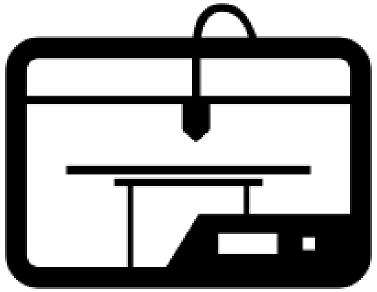
2. TRANSLATING TO PRINTER CODE



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

g-code →

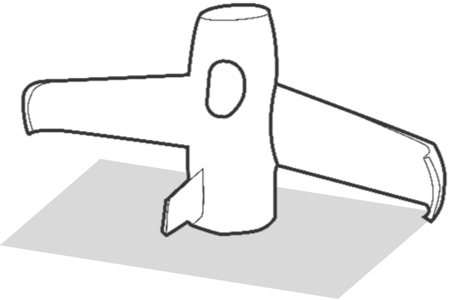
3. PRINTING HARDWARE & MATERIALS



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

Wait... →

4. EXAMINING PRINT & POST-PROCESSING



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

5. ITERATING & CREATING MORE MODELS

Slide based on Huaishu Peng's job talk; See also: https://www.3dhubs.com/knowledge-base/additive-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?

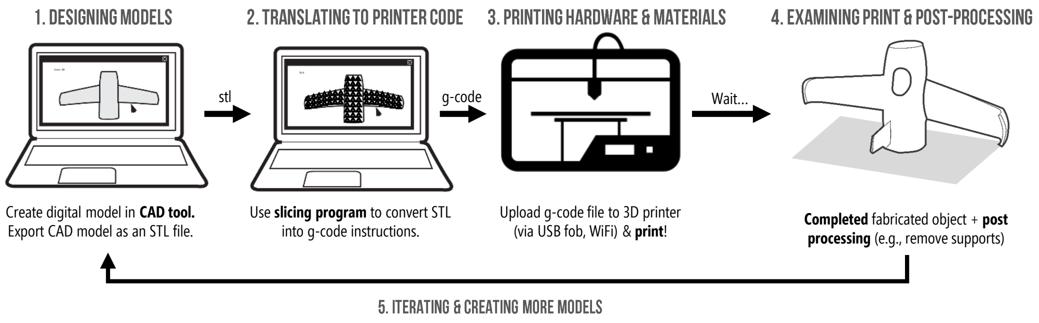
How can we fundamentally **transform the CAD** experience?

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

MOST 3D-PRINTED OBJECTS ARE STATIC “TRINKETS”

Source: slide courtesy of Huaishu Peng

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?

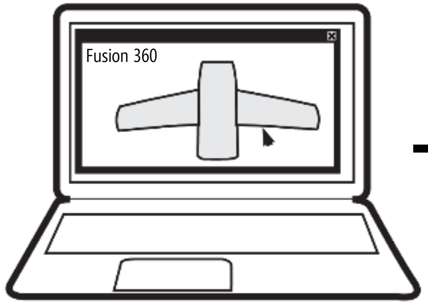
HOW TO CREATE DEFORMABLE 3D-PRINTED OBJECTS

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)?

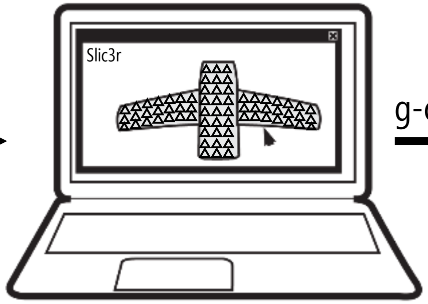
1. DESIGNING MODELS



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

stl →

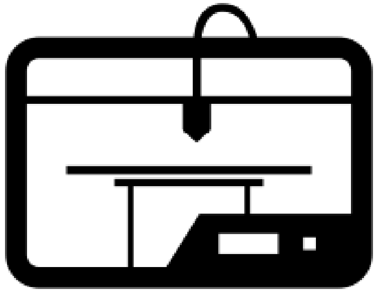
2. TRANSLATING TO PRINTER CODE



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

g-code →

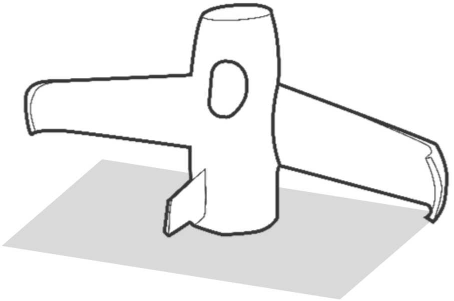
3. PRINTING HARDWARE & MATERIALS



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

Wait... →

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 Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch
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ABSTRACT
Recently, researchers started to engineer not only the outer shape of objects, but also their *internal microstructure*. Such objects, typically based on 3D cell grids, 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 the cells of which play together in a well-defined way in order to achieve macroscopic movement. 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 objects. To help users verify their designs during editing, our editor allows users to apply forces and simulates 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 external shape of 3D objects [36]. In order to add functionality to 3D printed objects, researchers integrated electronics [28], even printed optics [37], or loudspeakers [11].

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

ACM 978-1-4503-4189-9/16/10...$15.00
DOI: http://dx.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 of cells that together implement handle, latch, and springs. (b) Turning the handle causes the central hinge array to deform and to pull the latch inwards, which unlocks the door. (c) We created this mechanism in our custom editor. Here, we placed two hinge arrays that mechanically couple the handle to the latch, and cells that couple to the doorframe.

Researchers also started to design the inside of 3D objects by changing the structure of the 3D printed object itself. Initial projects optimized only a single parameter, such as the object's strength-to-weight ratio [14] or the position of the object's center of mass [26].

Recently, researchers started to push internal structures even further and created objects that consist internally of large numbers of 3D cells organized on a regular grid [30]. Since these objects allow each cell to be designed differently, the resulting objects literally offer thousands of degrees of freedom. These types of structures have also been referred to as *metamaterials*. Metamaterials are artificial

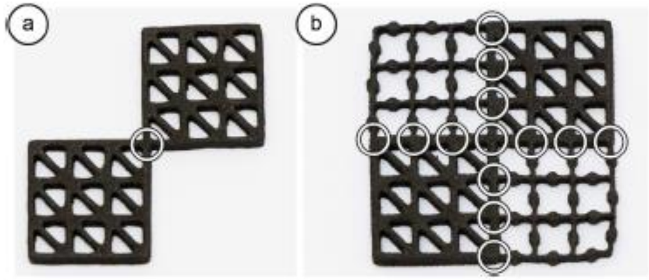

Figure 5: (a) A naïve living hinge, (b) reinforced with two arrays of hinges. To showcase the deformation, we laser cut these structures from rubber foam.

Figure 6: 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).

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

Source: Ion *et al.*, Metamaterial Mechanisms, UIST'16

METAMATERIAL MECHANISMS

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


metamaterial
MECHANISMS
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DIGITAL MECHANICAL METAMATERIALS

Digital Mechanical Metamaterials

Alexandra Ion, Ludwig Wall, Robert Kovacs, and Patrick Baudisch
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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 thus do not require assembly. We are building on 3D printed cell structures, also known as *metamaterials*. 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 signal propagation. We extend this basic mechanism 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.

Figure 1: (a) This combination door lock is implemented as a *digital mechanical metamaterial*, i.e., a single block of material based on a regular grid of cells. It allows users to input a numeric code, it processes the code, checks its correctness, and unlocks the latch. (b) Under the hood, the lock consists of an array of cells that transmit and process a mechanical signal.

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 this further, researchers created objects that consist internally of a large number of 3D 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].

CHI 2017, May 06 - 11, 2017, Denver, CO, USA

ACM 978-1-4503-4655-9/17/05…$15.00
DOI: http://dx.doi.org/10.1145/3025453.3025624

While metamaterials were initially understood as materials, we recently proposed to think of them as *machines;* such metamaterial mechanisms [10] consist of a single block of material, the cells of which play together in a well-defined way in order to achieve macroscopic movement. We used this principle previously to implement simple mechanical objects, such as a door latch (Figure 7).

Such *analog* machines, however, are limited in terms of complexity. As forces are passed on from one cell to the next, they are damped and the activation energy dissipates, causing the mechanical "signal" to decay exponentially. This limits the number of mechanisms that can be concatenated and therefore the complexity of the machine.

In this paper, we explore how to extend this concept towards *digital* mechanisms. Combining metamaterial mechanisms [10] with concepts from mechanical computing and mechanical signal propagation [16, 23], we introduce a new type of cell that propagates a digital mechanical signal, i.e., it counteracts signal decay and thus allows signals to pass through an *arbitrary* number of cells. We extend this basic mechanism to implement simple logic functions.

To illustrate this concept, Figure 1 shows a combination lock implemented using digital metamaterials. The device offers ten digit buttons on the front. Users tap these buttons to enter their code, then press the 'open' button to unlock the door.

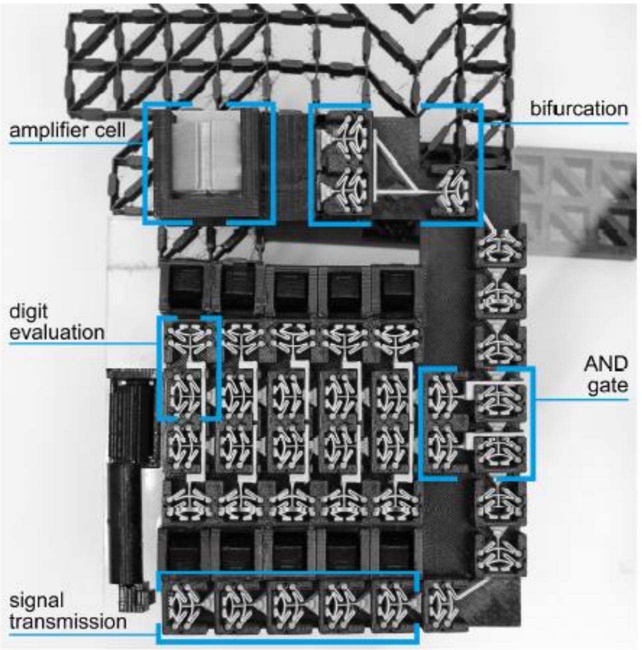

Figure 5: Our door lock consists of 82 cells, which implement the signal transmisison, the evaluation of each digit input by the user, an AND gate, and one amplifier cell with a pre-amplification step to move the blocking bolts sufficiently.

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

Source: Ion *et al.*, Digital Mechanical Metamaterials, CHI'17

DIGITAL MECHANICAL METAMATERIALS

Source: Ion *et al.*, CHI'17; https://youtu.be/Jx5-Kb4_VKU


digital mechanical
METAMATERIALS
Alexandra Ion, Ludwig Wall, Robert Kovacs, Patrick Baudisch
HPI
Hasso
Plattner
Institut

EMBEDDING SPRING-BASED STRUCTURES

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

Liang He[1,4] Huaishu Peng[3] Joshua Land[2] Mark D. Fuge[2] Jon E. Froehlich[1,4]

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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 create deformable 3D-printed objects. We propose 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

Additive manufacturing, or 3D printing, has moved beyond simply fabricating the shape of a 3D geometry. 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 block of shear cells printed with flexible material 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). Thus, we believe that springs have the potential to achieve different types of expressive deformation behaviors compared to other mechanical structures (*e.g.,* joints and metamaterials). However, manually designing embedded spring structures is not intuitive because deflections are mixed in the coil structure. To design and print specified functions, the spring deformation behaviors need to be decoupled.

In this poster paper, we contribute an initial design space of possible spring-based structures that constrain different types of printable deformation behaviors. We decouple spring behaviors into three individual categories: *stretch and/or compress*, *bend*, and *twist*. Each of the single-deformation springs are printed with a standard helical spring structure and an integrated constraint structure at the center. The resulting 3D-printed object can achieve *stretch/compress-only*, *bend-only* and *twist-only* deformations. The decoupled spring structures can be further combined for more complex behaviors such as *compress+twist* deformations.

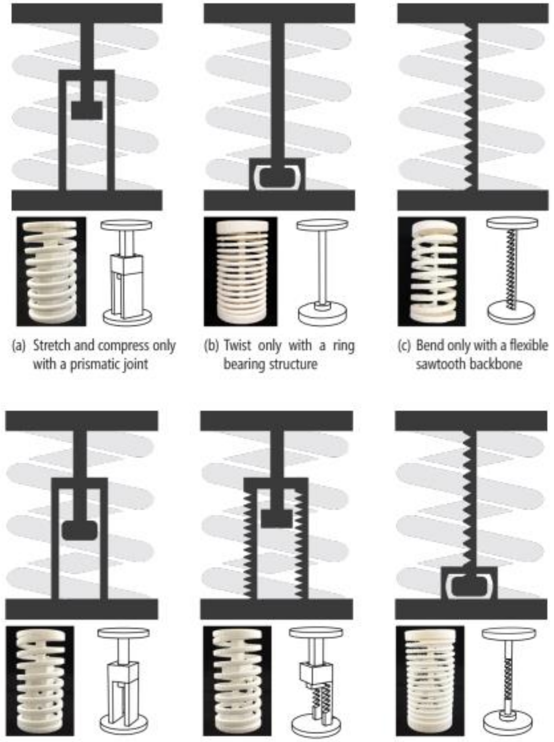
DESIGN SPACE

Informed by prior work [4, 5] and mechanical spring theory [1], we designed three basic single-deformation structures—*stretch and compress*, *bend*, and *twist*—and all possible combinations (Figure 2). The constraint structure for each deformation differs. For *linear deformations*, we designed a prismatic joint to limit the spring's bending and

Figure 1. Tigger example with three types of deformable tails: (a) sketch and compress only; (b) bend only; and (c) twist only (black marked dots show the rotation).

UIST '17 Adjunct, October 22–25, 2017, Quebec City, QC, Canada

ACM ISBN 978-1-4503-5419-6/17/10. https://doi.org/10.1145/3131785.3131836



(a) Stretch and compress only with a prismatic joint

(b) Twist only with a ring bearing structure

(c) Bend only with a flexible sawtooth backbone

(d) Linear + twist with a cylindrical joint

(e) Linear + bend with a prismatic joint and a sawtooth beam

(f) Twist + bend with a ring bearing and a toothsaw beam

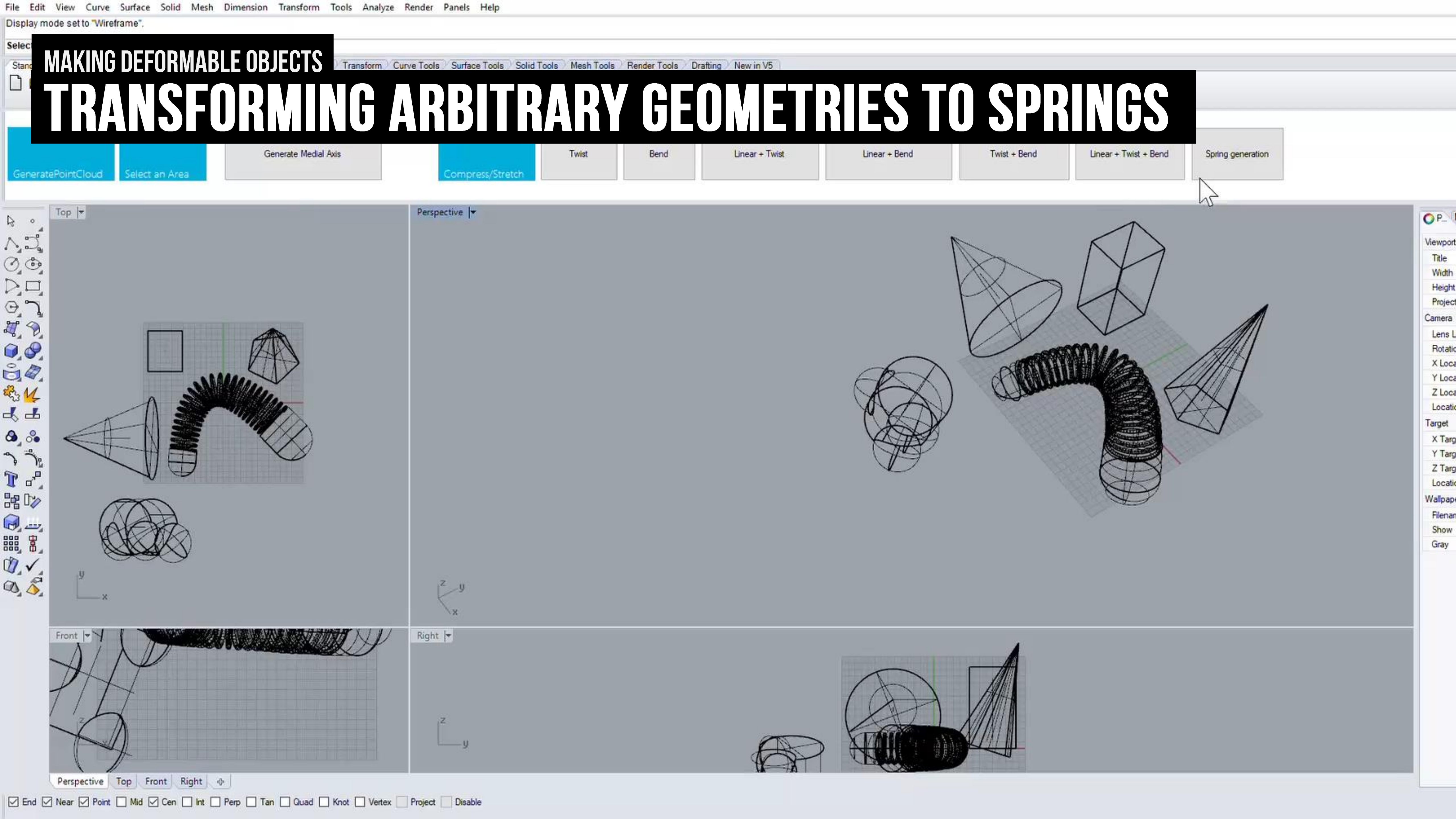
Select part geometries and convert to spring-based structures

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.

MAKING DEFORMABLE OBJECTS

TRANSFORMING ARBITRARY GEOMETRIES TO SPRINGS



PROJECT ONDULÉ: EXAMPLE DEFORMATIONS

ORIGINAL PRINT

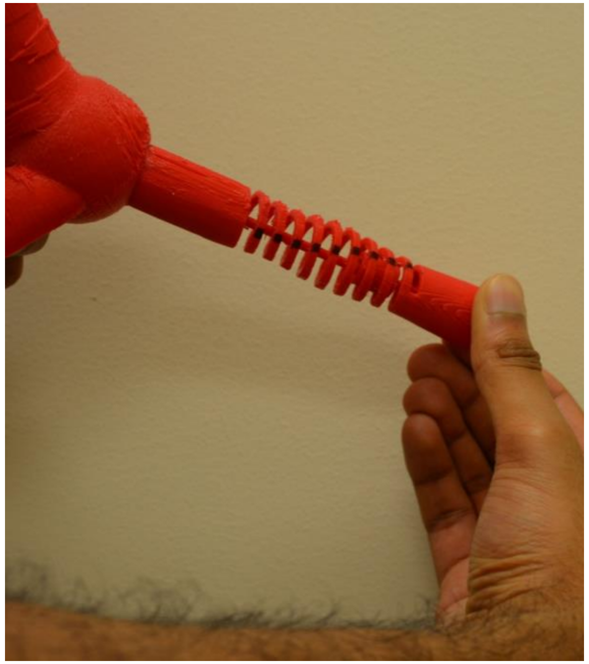
Tigger with traditional helical spring

DESIGN #1: BEND ONLY

Helical spring with embedded flexible sawtooth backbone

DESIGN #2: LINEAR ONLY

Helical spring with a prismatic joint

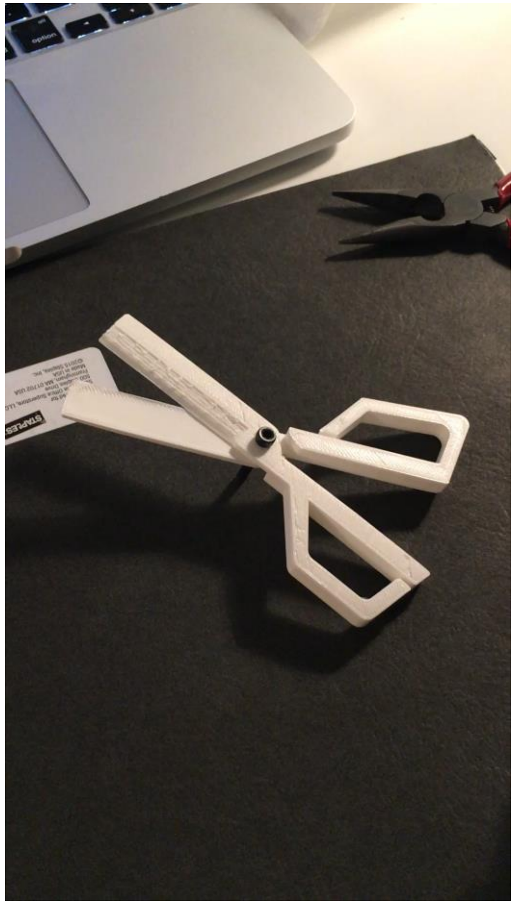


DESIGN #3: TWIST ONLY

Helical spring with a ring bearing structure

Source: He *et al.*, UIST'17; He *et al.*, SCF'17

PROJECT ONDULÉ: ACCESSIBILITY APPLICATIONS

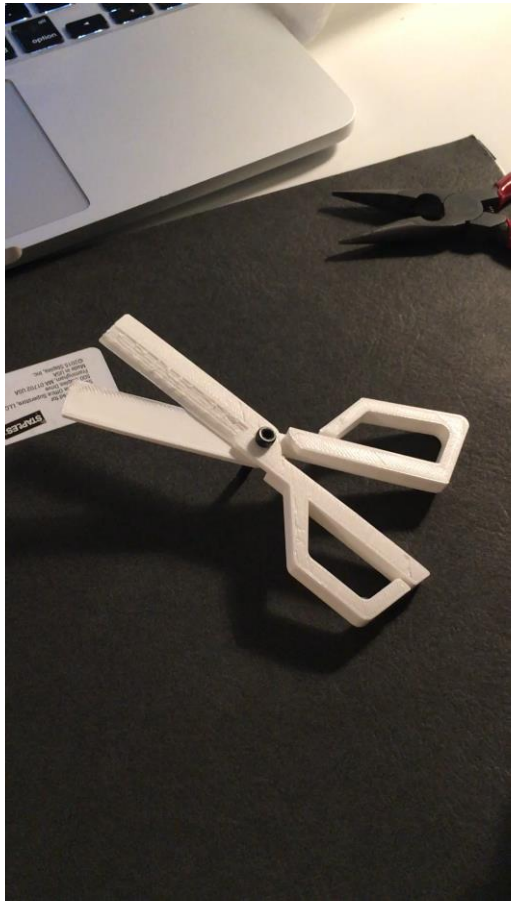


TRADITIONAL SCISSORS

Requires fine motor abilities

Source: He *et al.*, UIST'17; He *et al.*, SCF'17

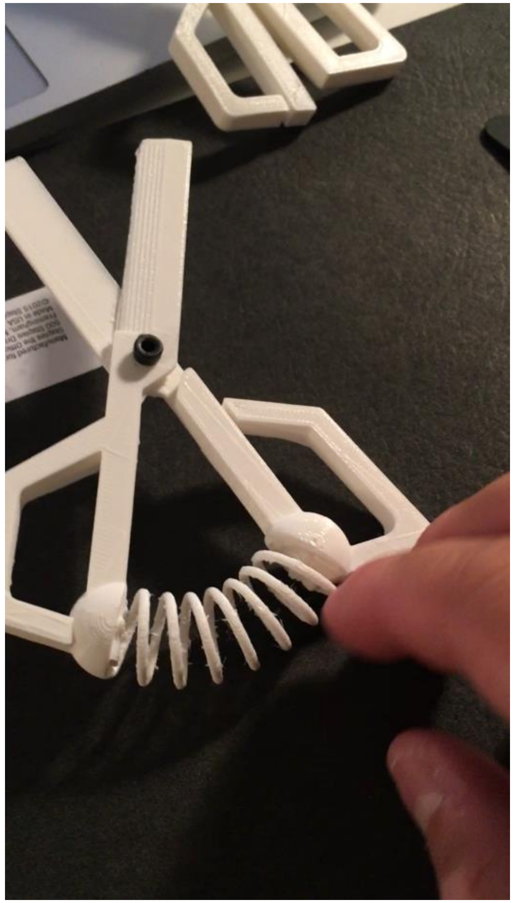
PROJECT ONDULÉ: ACCESSIBILITY APPLICATIONS



TRADITIONAL SCISSORS

Requires fine motor abilities

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

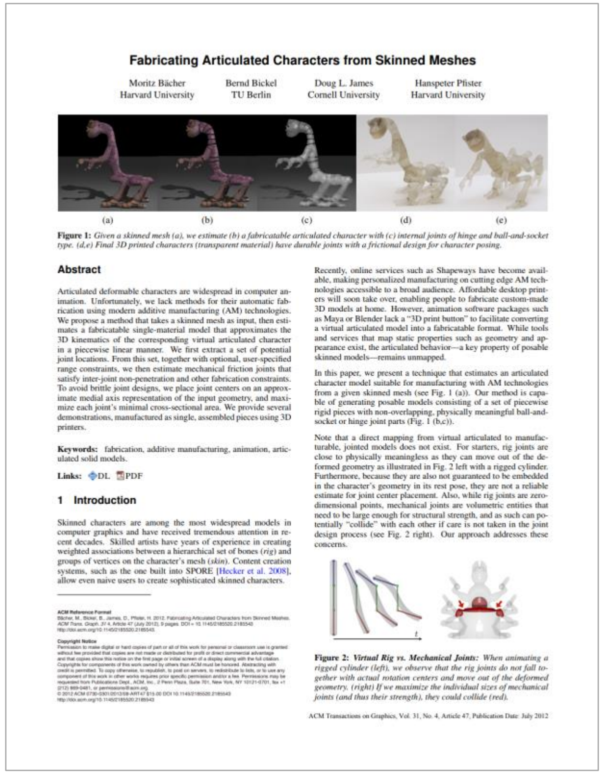


SPRING SCISSORS

Spring automatically reopens scissors after a cut

Source: He *et al.*, UIST'17; He *et al.*, SCF'17

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

(a) (b) (c) (d) (e)

Figure 1: *Given a skinned mesh (a), we estimate (b) a fabricatable 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 method that takes a skinned mesh as input, then estimates 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. From this set, together with optional, user-specified range constraints, we then estimate mechanical friction joints that satisfy inter-joint non-penetration and other fabrication constraints. To avoid brittle joint designs, we place joint centers 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 (*rig*) and groups of vertices on the character's mesh (*skin*). Content creation systems, such as the one built into SPORE [Hecker et al. 2008], allow even naive users to create sophisticated skinned characters.

ACM Reference Format
Bächer, M., Bickel, B., James, D., Pfister, H. 2012. Fabricating Articulated Characters from Skinned Meshes. ACM Trans. Graph. 31 4, Article 47 (July 2012), 9 pages. DOI = 10.1145/2185520.2185543 http://doi.acm.org/10.1145/2185520.2185543.

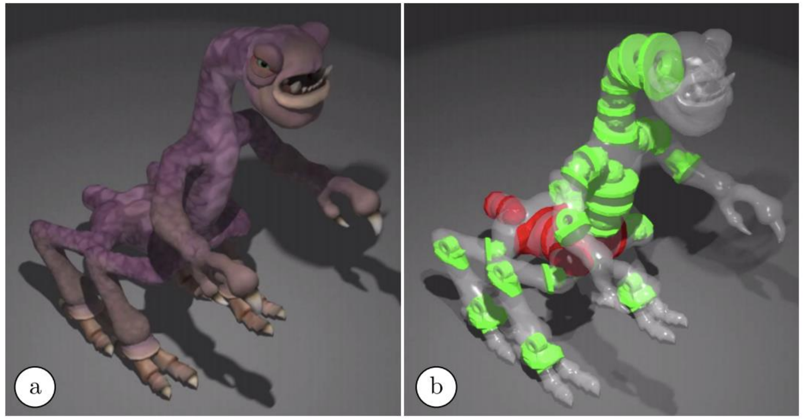
Recently, online services such as Shapeways have become available, making personalized manufacturing on cutting edge AM technologies accessible to a broad audience. Affordable desktop printers will soon take over, enabling people to fabricate custom-made 3D models at home. However, animation software packages such as Maya or Blender lack a "3D print button" to facilitate converting a virtual articulated model into a fabricatable format. While tools and services that map static properties such as geometry and appearance exist, the articulated behavior—a key property of posable skinned models—remains unmapped.

In this paper, we present a technique that estimates an articulated character model suitable for manufacturing with AM technologies from a given skinned mesh (see Fig. 1 (a)). Our method is capable of generating posable models consisting of a set of piecewise rigid pieces with non-overlapping, physically meaningful ball-and-socket or hinge joint parts (Fig. 1 (b,c)).

Note that a direct mapping from virtual articulated to manufacturable, jointed models does not exist. For starters, rig joints are close to physically meaningless as they can move out of the deformed geometry as illustrated in Fig. 2 left with a rigged cylinder. Furthermore, because they are also not guaranteed to be embedded in the character's geometry in its rest pose, they are not a reliable estimate for joint center placement. Also, while rig joints are zero-dimensional points, mechanical joints are volumetric entities that need to be large enough for structural strength, and as such can potentially "collide" with each other if care is not taken in the joint design process (see Fig. 2 right). Our approach addresses these concerns.

t

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).*

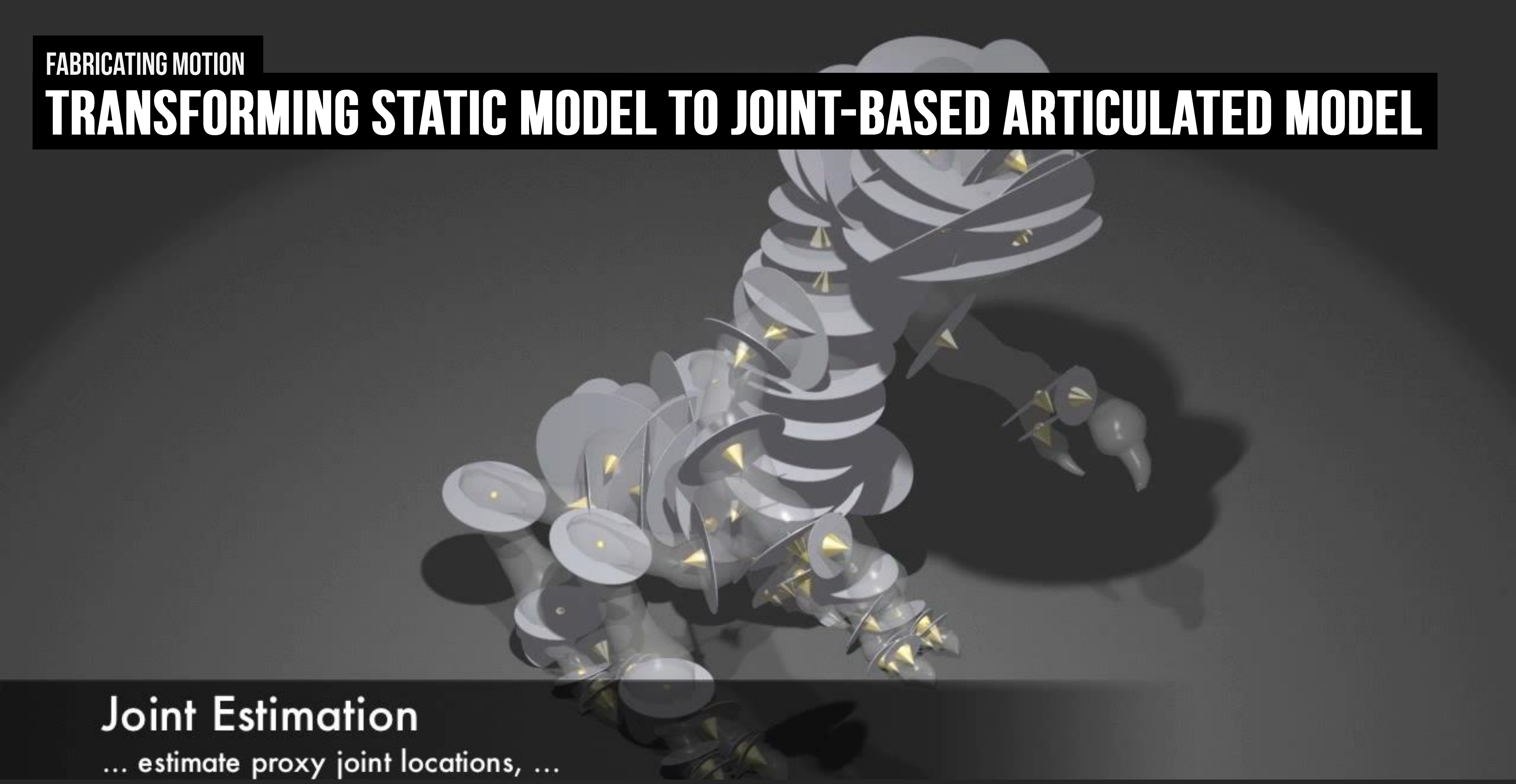


Takes static 3D model and automatically converts to a fabricatable single-material model with articulated motion using joints.

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

Source: Bächer *et al.*, Fabricating articulated characters from skinned meshes, ACM Trans. Graph. 2012

TRANSFORMING STATIC MODEL TO JOINT-BASED ARTICULATED MODEL



Source: Megaro *et al.*, ACM Trans. Graph.'17; https://youtu.be/IUe3mGkngs4

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 special 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 tools for telescopic design. We present a novel geometric characterization of telescoping curves, and explore how free-form surfaces can be approximated by networks of such curves. In particular we consider piecewise helical space curves with torsional impulses, which significantly generalize the linear telescopes found in typical engineering designs. Based on this principle we develop a system for computational design and fabrication which allows users to explore the space of telescoping structures; inputs to our system include user sketches or arbitrary meshes, which are then converted to a curve skeleton. We prototype applications in animation, fabrication, and robotics, using 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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DOI: http://dx.doi.org/10.1145/3072959.3073673

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), 9 pages.
DOI: http://dx.doi.org/10.1145/3072959.3073673

1 INTRODUCTION

A pirate's telescope, consisting of straight, nested cylinders, is a familiar sight commonly 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 (Garrette and Ryan 1969; McCord and Williford 1966). Deployable structures have more broadly become 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-bound vessels (Stinson 2014), or arterial stents that must travel through narrow passages during surgery (Kuribayashi et al. 2006). Generalized telescoping mechanisms likewise hold great promise for deployable design, providing a fundamentally new kind of joint that can be reshaped in surprising and entertaining ways. The design space of telescoping structures, however, remains relatively 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

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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.

Source: Yu *et al.*, Computational design of telescoping structures, ACM Trans. Graph. 2017

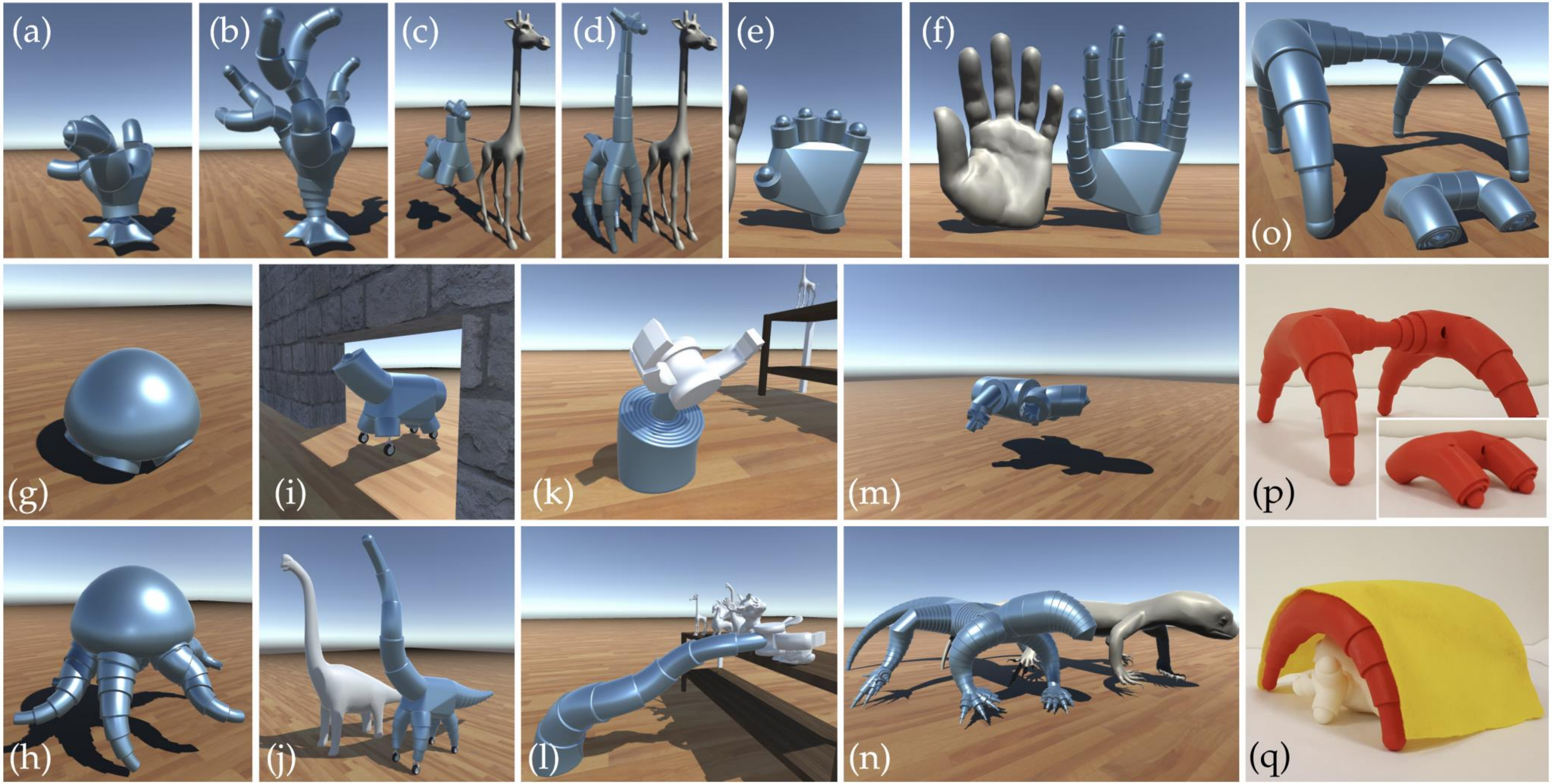
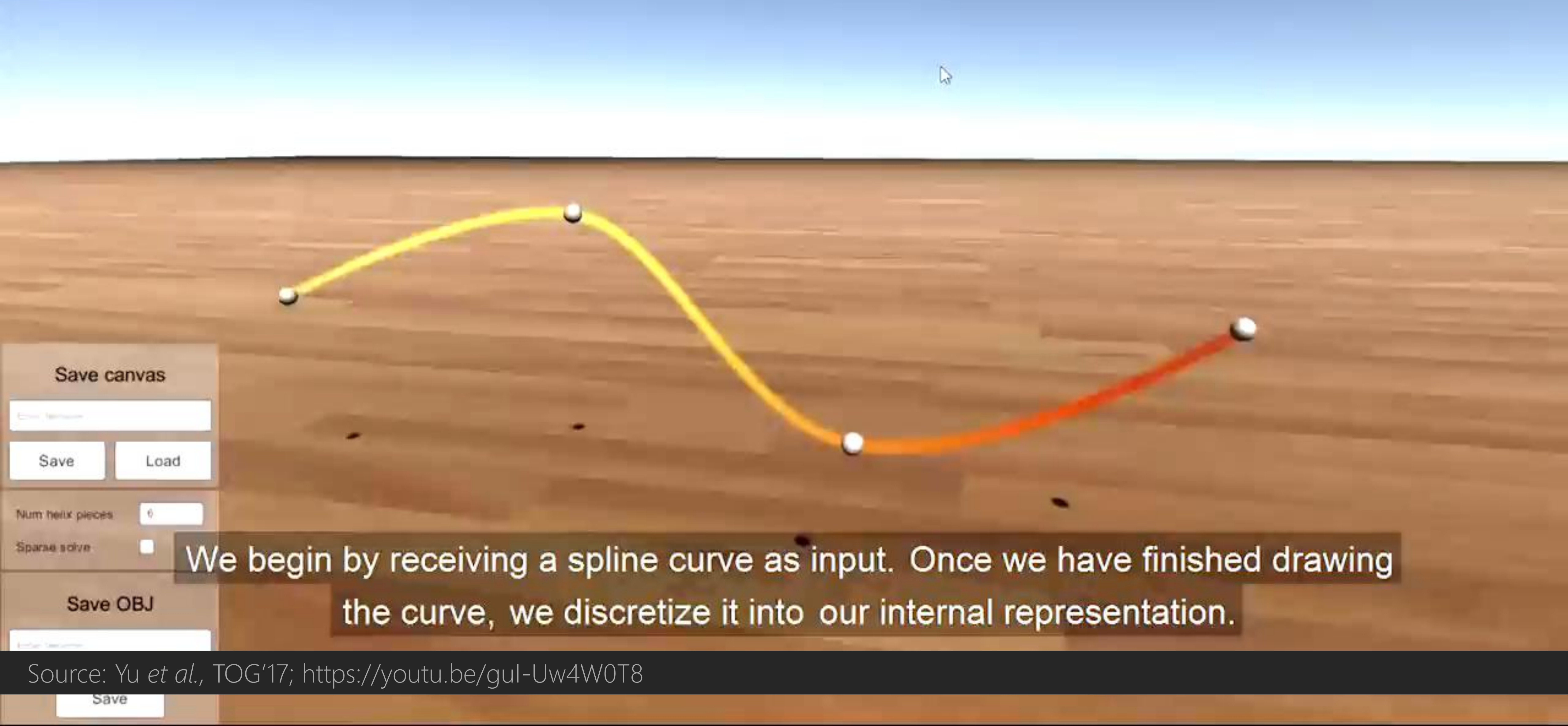


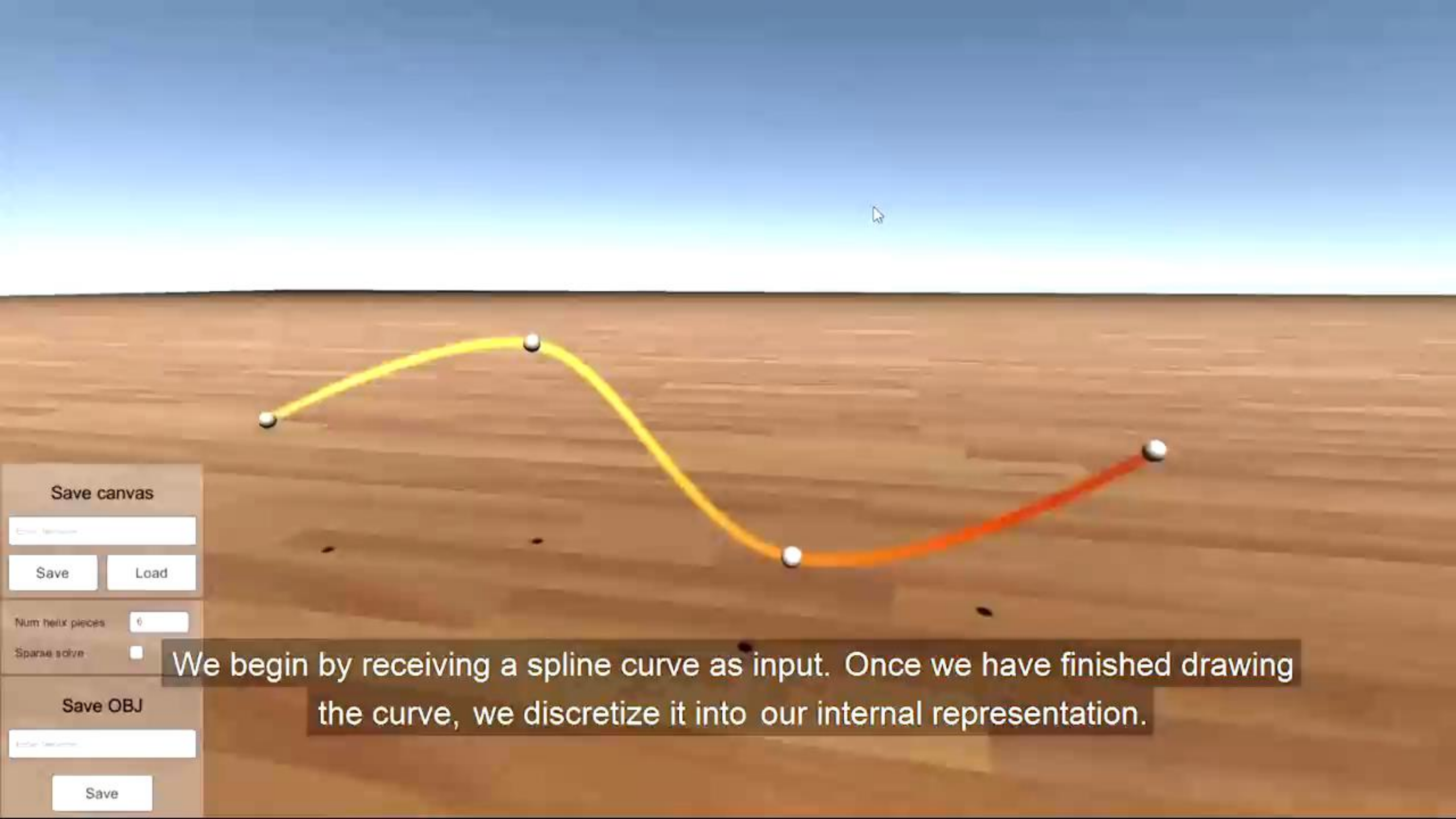
Fig. 13. Gallery of telescoping structures and applications. (a–b) Tree. (c–d) Giraffe. (e–f) Hand. (g–h) "Hexapus" with IK-driven tentacles. (i–j) Telescoping vehicular brachiosaurus. (k–l) Telescoping robotic crane driven by IK. (m–n) Lizard. (o–q) Deployable shelter housing the armadillo from Fig.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

MAKING DEFORMABLE OBJECTS

DESIGNING TELESCOPING STRUCTURES



Source: Yu *et al.*, TOG’17; https://youtu.be/guI-Uw4W0T8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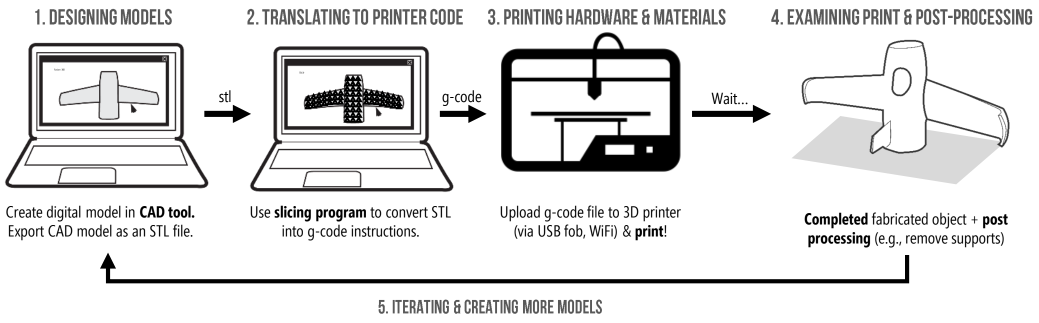
We begin by receiving a spline curve as input. Once we have finished drawing
the curve, we discretize it into our internal representation.

HOW TO CREATE KINEMATIC 3D-PRINTED OBJECTS



As before, 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 **kinematic** 3D-printed objects?

DESIGNING “COMPLIANT” MECHANISMS

A Computational Design Tool for Compliant Mechanisms

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MORITZ BÄCHER, 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 defining the topology of the compliant design. This input 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 technical core of our approach, we describe a number of objectives that shape the design space in a meaningful way, including trajectory matching, collision avoidance, lateral stability, resilience to failure, and minimizing motor torque. Optimal designs in this space are obtained as solutions to an equilibrium-constrained minimization problem 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 animatronics, and verify the feasibility of our designs by manufacturing 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

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Vittorio Megaro, Jonas Zehnder, Moritz Bächer, 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/http://dx.doi.org/10.1145/3072959.3073636

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1 INTRODUCTION

Engineers routinely design for strength and stiffness. Steel and concrete prevent deflections in buildings, and machines resort to rigid articulation in order to avoid deformations. But although most human designs are inspired by Nature, rigidity is a concept foreign to the living world: from a kangaroo's legs to the wings of a bat—bones, tendons, and cartilage are the nuts and bolts of organic machines, and deformation is an integral part of the design, crucial for both efficiency and robustness. Unfortunately, designing for flexibility requires deep understanding and precise predictions of finite deformations, which proves to be substantially more difficult than relying on rigidity.

Fueled by progress in technology and computation, however, many fields of engineering have started to *embrace deformation* and to leverage flexibility for better, more elegant, and ultimately more satisfying designs. Applied to machines, this turn to the flexible leads to *compliant mechanisms*, i.e., mechanical devices that perform motion not through rigid articulation but by virtue of elastically deforming flexures. Compliant mechanisms enjoy widespread use in industry, where they are valued for their accuracy, ease of manufacturing, scalability, and cost efficiency. The spectrum ranges from specialized microelectromechanical systems (MEMS) for miniature sensors and actuators [Kota et al. 2001], to more mundane devices including monolithic pliers and wiper blades, and to commonplace products such as binder clips, backpack latches, and shampoo lids.

We are primarily interested in exploring the potential of compliant mechanisms for personalized automata 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

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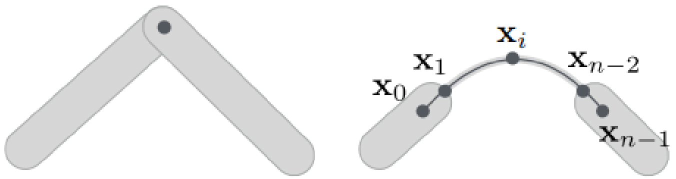


Fig. 2. **Conventional vs. compliant hinge.** We replace conventional joints (left) with a single or several flexures (right).

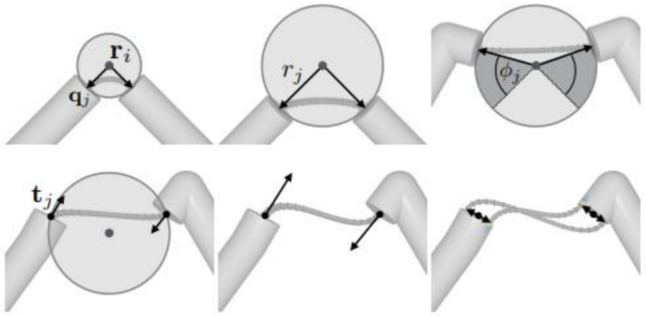


Fig. 3. Parameterizing a compliant hinge with two offset flexures.

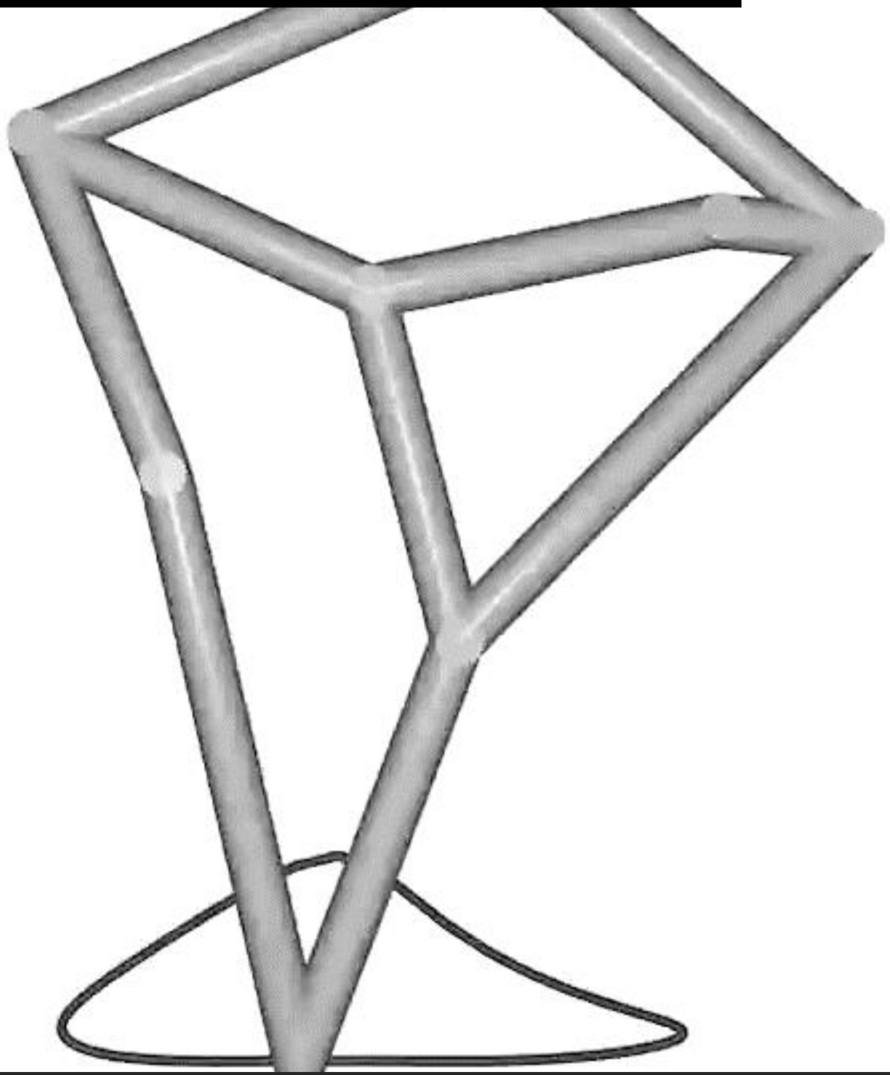
Presents a computational tool for designing compliant mechanisms to control motion behaviors.

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

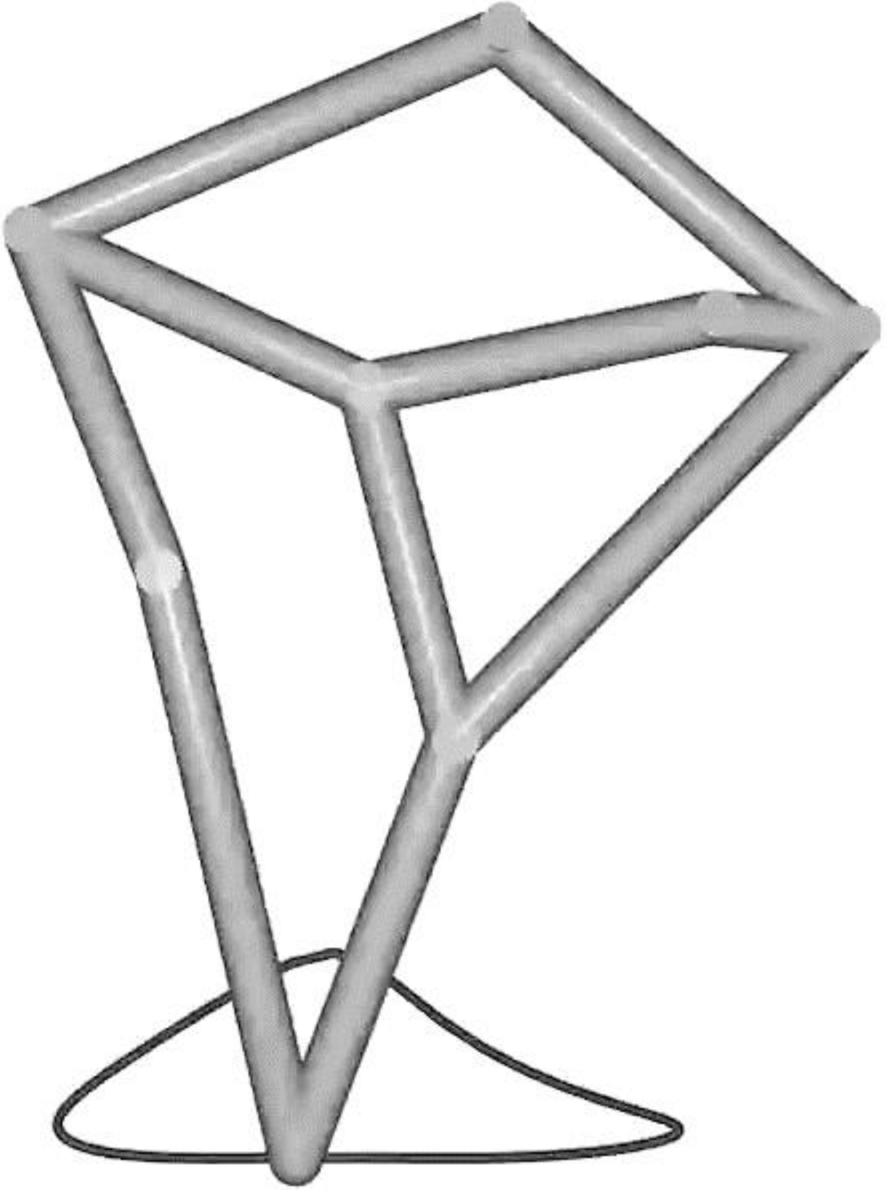
Explores design space, optimizations, resilience to failure, and verifies feasibility by creating a variety of physical prototypes.

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

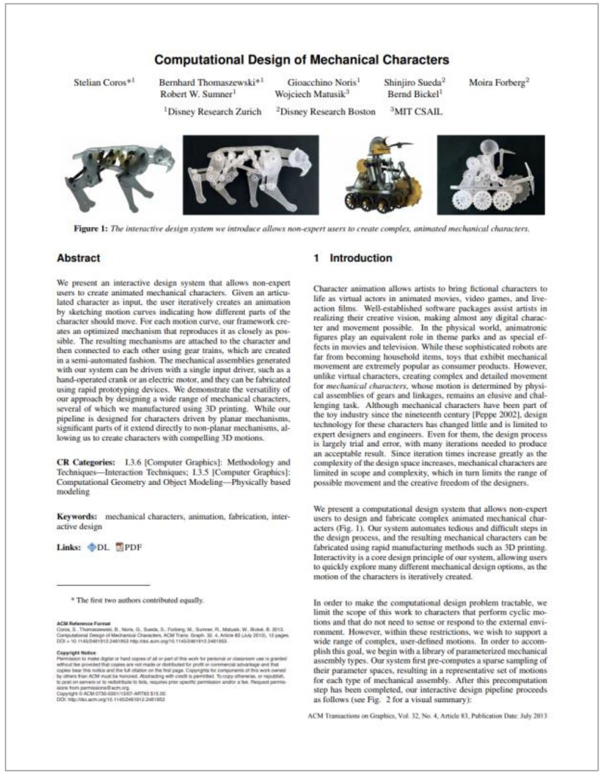
DESIGNING "COMPLIANT" MECHANISMS



Source: Megaro *et al.*, ACM Trans. Graph.'17; https://youtu.be/IUe3mGkngs4



DESIGNING MECHANICAL CHARACTERS



Computational Design of Mechanical Characters

Stelian Coros*[1] Bernhard Thomaszewski*[1] Gioacchino Noris[1] Shinjiro Sueda[2] Moira Forberg[2] Robert W. Sumner[1] Wojciech Matusik[3] Bernd Bickel[1]

[1]Disney Research Zurich [2]Disney Research Boston [3]MIT 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 sketching motion curves indicating how different parts 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 attached to the character and then connected to each other using gear trains, which are created in a semi-automated fashion. The mechanical assemblies generated with our system can be driven with a single input driver, such as a hand-operated crank or an electric motor, and they can be fabricated using rapid prototyping devices. We demonstrate the versatility of our approach by designing a wide range of mechanical characters, several 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.

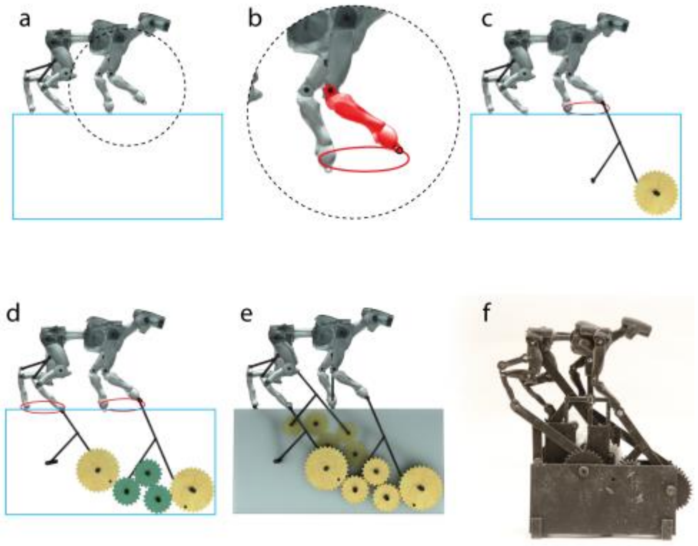
1 Introduction

Character animation allows artists to bring fictional characters to life as virtual actors in animated movies, video games, and live-action films. Well-established software packages assist artists in realizing their creative vision, making almost any digital character and movement possible. In the physical world, animatronic figures play an equivalent role in theme parks and as special effects in movies and television. While these sophisticated robots are far from becoming household items, toys that exhibit mechanical movement are extremely popular as consumer products. However, unlike virtual characters, creating complex and detailed movement for *mechanical characters*, whose motion is determined by physical assemblies of gears and linkages, remains an elusive and challenging task. Although mechanical characters have been part of the toy industry since the nineteenth century [Peppe 2002], design technology for these characters has changed little and is limited to expert designers and engineers. Even for them, the design process is largely trial and error, with many iterations needed to produce an acceptable result. Since iteration times increase greatly as the complexity of the design space increases, mechanical characters are limited in scope and complexity, which in turn limits the range of possible movement and the creative freedom of the designers.

We present a computational design system that allows non-expert users to design and fabricate complex animated mechanical characters (Fig. 1). Our system automates tedious and difficult steps in the design process, and the resulting mechanical characters can be fabricated using rapid manufacturing methods such as 3D printing. Interactivity is a core design principle of our system, allowing users to quickly explore many different mechanical design options, as the motion of the characters is iteratively created.

In order to make the computational design problem tractable, we limit the scope of this work to characters that perform cyclic motions and that do not need to sense or respond to the external environment. However, within these restrictions, we wish to support a wide range of complex, user-defined motions. In order to accomplish this goal, we begin with a library of parameterized mechanical assembly types. Our system first pre-computes a sparse sampling of their parameter spaces, resulting in a representative set of motions for each type of mechanical assembly. After this precomputation step has been completed, our interactive design pipeline proceeds as follows (see Fig. 2 for a visual summary):

ACM Transactions on Graphics, Vol. 32, No. 4, Article 83, Publication Date: July 2013



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

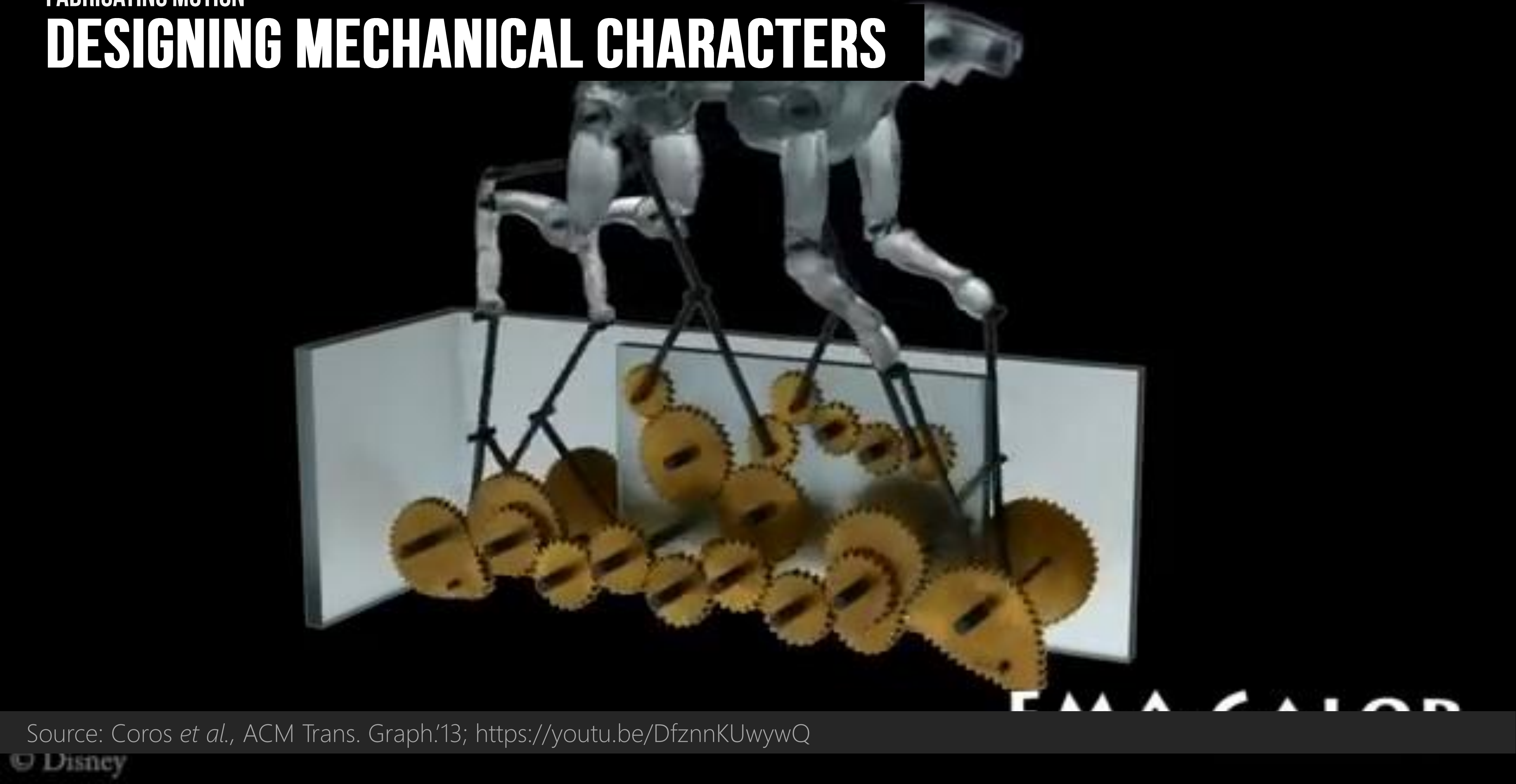
User specifies motion curve and tool auto-generates gear assembly to mimic motion

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

Source: Coros *et al.*, Computational design of mechanical characters, ACM Trans. Graph. 2013

FABRICATING MOTION

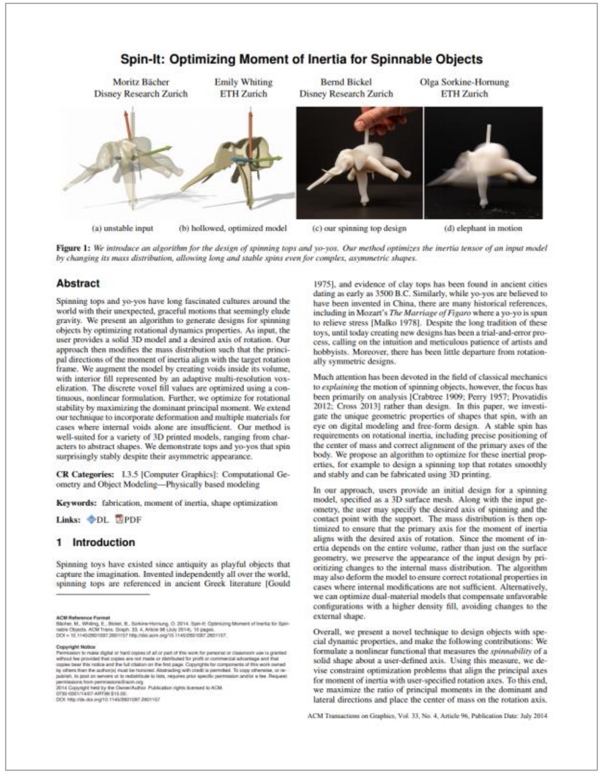
DESIGNING MECHANICAL CHARACTERS



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

(a) unstable input (b) hollowed, optimized model (c) our spinning top design (d) elephant in motion

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 elude gravity. We present an algorithm to generate designs for spinning objects by optimizing rotational dynamics properties. As input, the user provides a solid 3D model and a desired axis of rotation. Our approach then modifies the mass distribution such that the principal directions of the moment of inertia align with the target rotation frame. We augment the model by creating voids inside its volume, with interior fill represented by an adaptive multi-resolution voxelization. The discrete voxel fill values are optimized using a continuous, nonlinear formulation. Further, we optimize for rotational stability by maximizing the dominant principal moment. We extend our technique to incorporate deformation and multiple materials for cases where internal voids alone are insufficient. Our method is well-suited for a variety of 3D printed models, ranging from characters to abstract shapes. We demonstrate tops and yo-yos that spin surprisingly stably despite their asymmetric appearance.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling

Keywords: fabrication, moment of inertia, shape optimization

Links: DL PDF

1 Introduction

Spinning toys 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 in Mozart's *The Marriage of Figaro* where a yo-yo is spun to relieve stress [Malko 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 departure 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 primarily on analysis [Crabtree 1909; Perry 1957; Provatidis 2012; Cross 2013] rather than design. In this paper, we investigate the unique geometric properties of shapes that spin, with an eye on digital modeling and free-form design. A stable spin has requirements on rotational inertia, including precise positioning 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, for example to design a spinning top that rotates smoothly and stably and can be fabricated using 3D printing.

In our approach, users provide an initial design for a spinning model, specified as a 3D surface mesh. Along with the input geometry, the user may specify the desired axis of spinning 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 moment of inertia depends on the entire volume, rather than just on the surface geometry, we preserve the appearance of the input design by prioritizing changes to the internal mass distribution. The algorithm may also deform the model to ensure correct rotational properties 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 special dynamic properties, and make the following contributions: We formulate a nonlinear functional that measures the *spinnability* of a solid shape about a user-defined axis. Using this measure, we devise constraint optimization problems that align the principal axes for moment of inertia with user-specified rotation axes. To this end, we maximize the ratio of principal moments in the dominant and lateral directions and place the center of mass on the rotation axis.

ACM Reference Format
Bächer, M., Whiting, E., Bickel, B., Sorkine-Hornung, O. 2014. Spin-It: Optimizing Moment of Inertia for Spinnable Objects. ACM Trans. Graph. 33, 4, Article 96 (July 2014), 10 pages. DOI = 10.1145/2601097.2601157 http://doi.acm.org/10.1145/2601097.2601157.

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

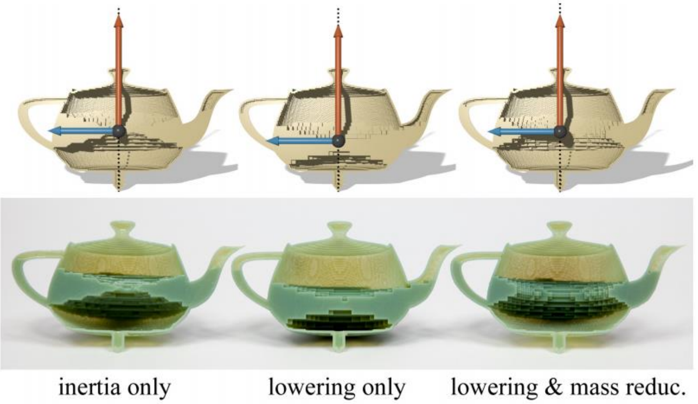
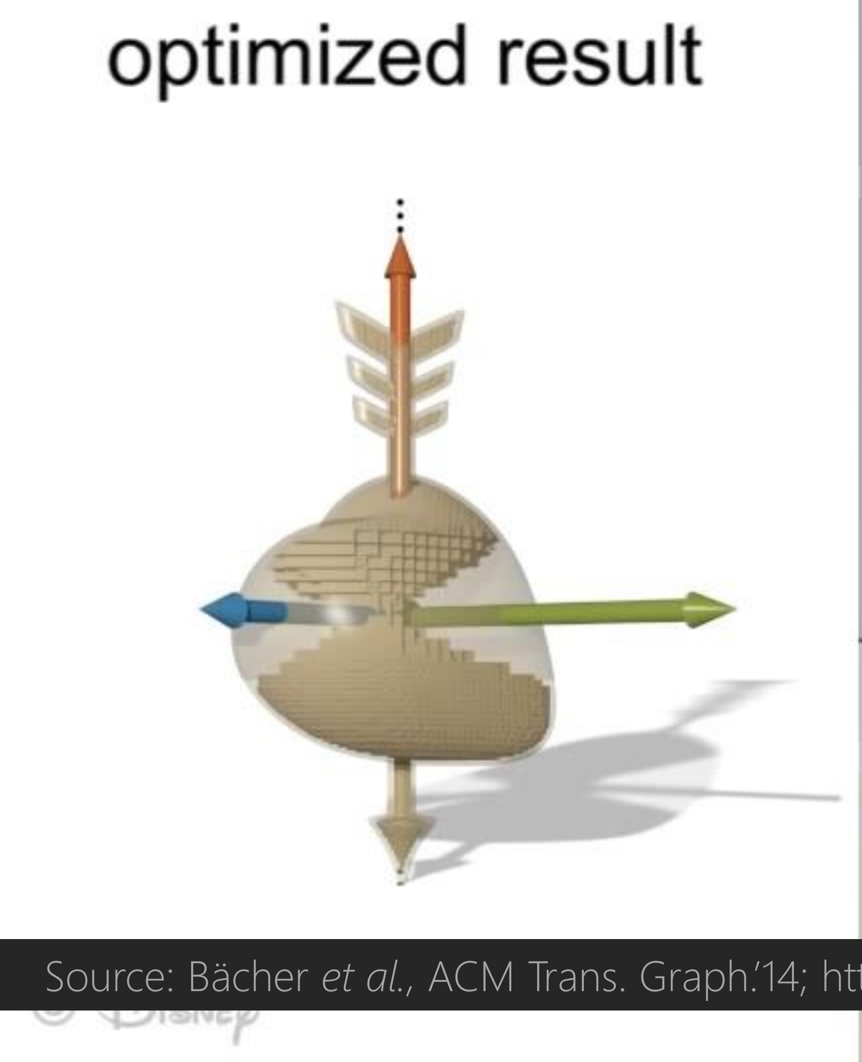


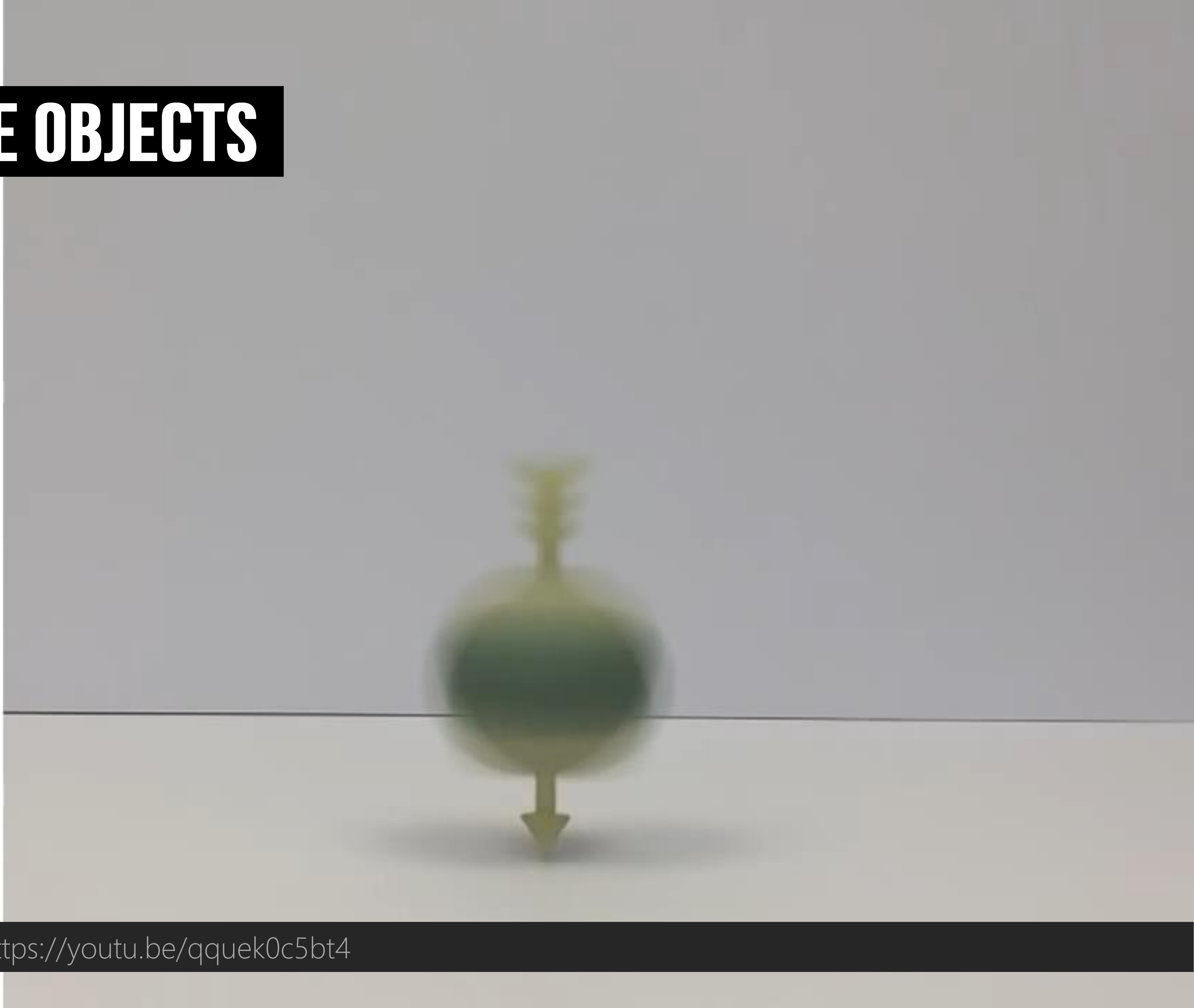
Figure 9: "*Teapot*": *(Left) Hollowed result showing voxelized interior mass and aligned axes using $f_{top} = f_{yo\text{-}yo}$. (Middle) Lowering of the center of mass shifts the mass distribution closer to the contact point. If we include mass reduction (right), mass is reduced inward out, resulting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

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

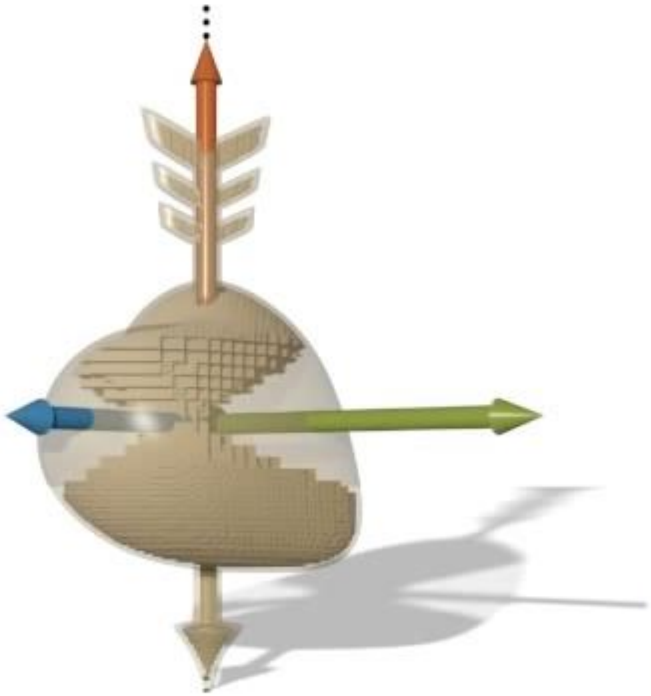
Validates approach via demonstration of models converted to tops and yo-yos

CREATING SPINNABLE OBJECTS



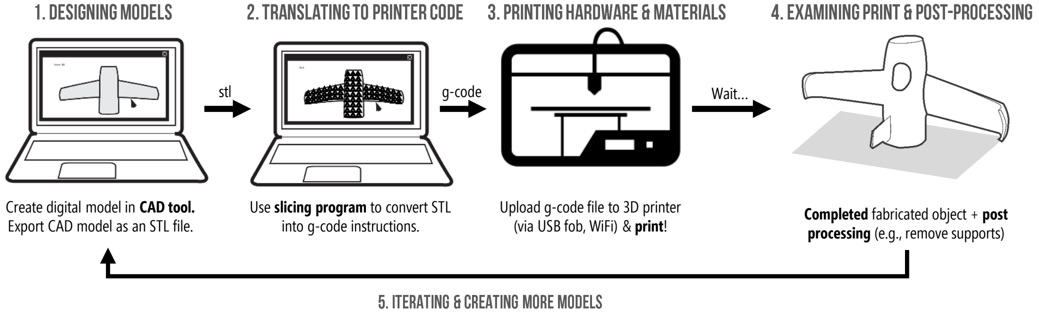


Source: Bächer *et al.*, ACM Trans. Graph.'14; https://youtu.be/qquek0c5bt4 optimized result



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

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a b c d

Figure 1. 3D printed electromagnetic devices. a) Solenoid used to actuate the cat hand; 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 *wound in place* coils. 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 this mechanism to form coils which induce magnetic fields as a current is passed through them. Soft iron wire can additionally be used to form components with high magnetic permeability which are thus able to shape and direct these magnetic fields to where they are needed. When fabricated with structural plastic elements, this allows simple but complete custom electromagnetic devices to be 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.

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ACM 978-1-4503-4189-9/16/10 $15.00
DOI: http://dx.doi.org/10.1145/2984511.2984523

Author Keywords

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

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): 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 optical components [30], speakers [11], hydraulic 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 inside printed objects to create simple electronic devices [24, 29, 17]. This opens 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 fabricate most functional devices needing actuators, but instead these required either assembly with, or addition of, pre-manufactured parts into a print.

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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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).

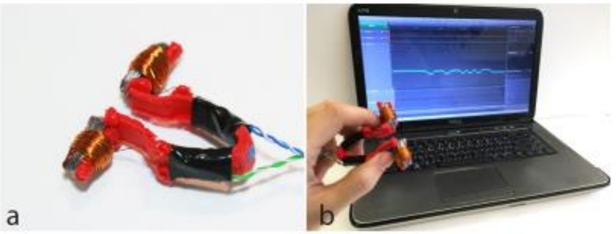
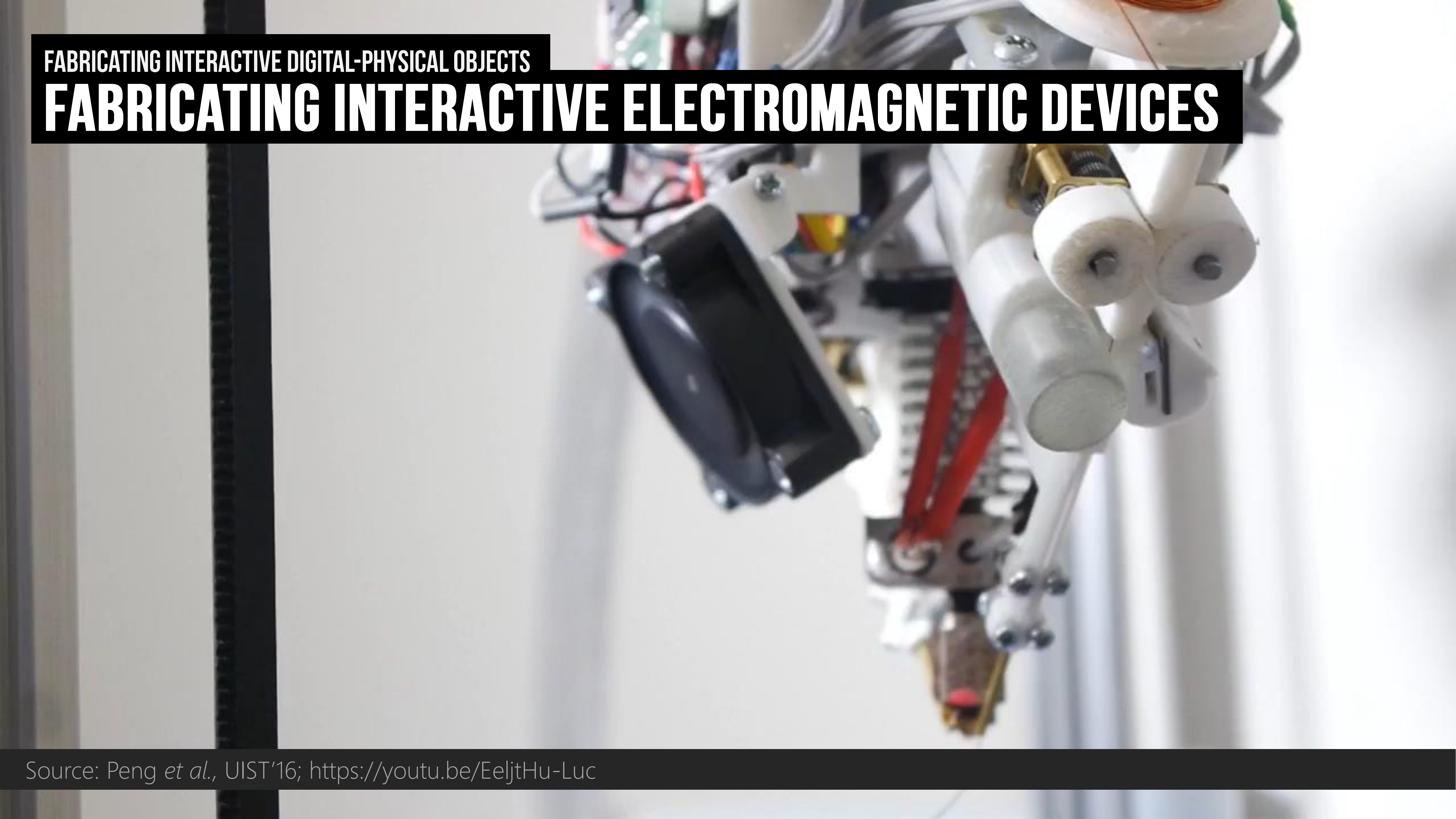


Figure 12. A printed coupling sensor. a) The sensor is made by printing two coils next to each other; b) By driving one coil with a square wave, we can infer distance between the two coils by observing the coupling strength.

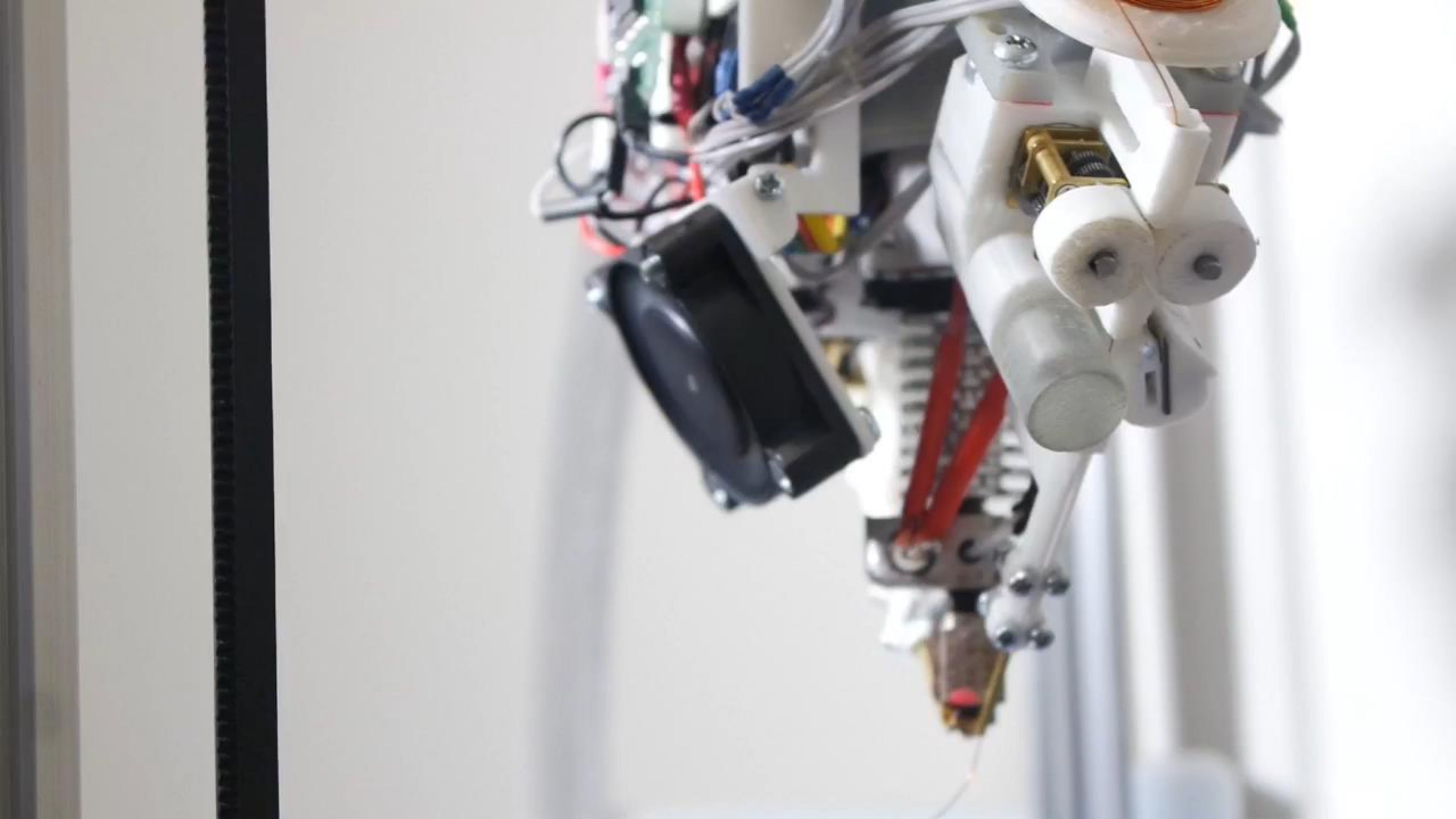
New fabrication pipeline (CAD + 3D printer) to print interactive electromechanical objects.

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

FABRICATING INTERACTIVE 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

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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 directly embedded in the casing or mechanical structure of an interactive device. Using these elements, unique display surfaces, novel illumination techniques, custom optical sensors, and embedded optoelectronic components can be digitally fabricated for rapid, high fidelity, highly customized 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.

INTRODUCTION

3D printing is becoming increasingly capable and affordable. We envision a future world where interactive devices can be printed rather than assembled; a world where a device with active components is created as a single object, rather than a case enclosing circuit boards and individually assembled parts (Figure 2). This capability has tremendous potential for rapid high fidelity prototyping, and eventually for production of customized devices tailored to individual needs and/or specific tasks. With these capabilities we envision it will be possible to design highly functional devices in a digital editor — importing components from a library of interactive elements, positioning and customizing them, then pushing 'print' to have them realized in physical form. In this paper we explore some of the possibilities for this vision afforded by today's 3D printing technology. Specifically, we describe an approach for using 3D printed optical elements, *Printed Optics*, as one category of components within a greater library of reusable interactive elements.

Custom optical elements have traditionally been expensive and impractical to produce due to the manufacturing precision and finishing required. Recent developments in 3D printing technology have enabled the fabrication of high resolution transparent plastics with similar optical properties to plexiglas™. One-off 3D printed optical elements can be designed and fabricated literally within minutes for significantly less cost than conventional manufacturing; greatly increasing accessibility and reducing end-to-end prototyping time. 3D printed optical elements also afford new optical form-factors that were not previously possible, such as fab-

589

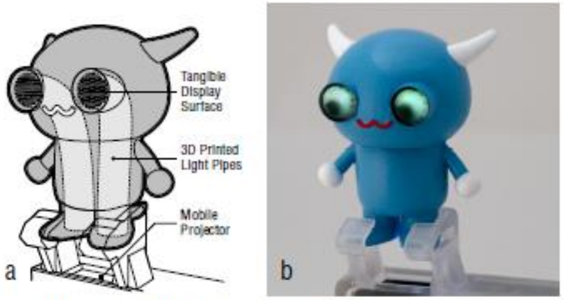

Figure 3: A 3D printed mobile projector accessory using embedded light pipes (a) to map a projected image onto a characters eyes (b).

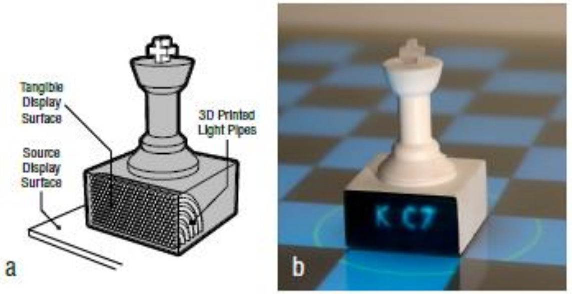

Figure 5: Light pipes are 3D printed inside tangible objects, such as chess pieces (a), to create additional display surfaces for tabletop interaction (b).

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

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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 interactivity into fabricated objects using soft, passive, low-cost bellow-like structures. 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. A microphone captures and identifies these air pulses enabling interactivity. We describe the underlying acoustic theory used to inform our design, an informal examination of the effect of different 3D-printed corrugations on air signatures, and our resulting SqueezaPulse implementation. To demonstrate and evaluate the potential of SqueezaPulse, we present four prototype 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; squeeze interactions; corrugated tube; air pulse.

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

DOI: http://dx.doi.org/10.1145/3024969.3024976

INTRODUCTION
Fabrication techniques such as 3D printing, laser cutting, and casting have been increasingly used to build physical prototypes in HCI. Incorporating interactive functions into fabricated objects, however, is still a cumbersome and highly decoupled process. In response, an emerging body of work aims to imbue fabricated objects with interactive capabilities throughout the rapid prototyping cycle, including via custom-designed optics [36], touch sensitive electronics [29], active acoustic-enabled structures [11], and precision sensors [35]. Building on this growing literature, we introduce *SqueezaPulse*, a technique for creating interactive fabricated objects using acoustic sensing without embedded circuitry, wiring, or power (Figure 1). Our novel approach shapes small puffs of air into identifiable but inaudible sound signatures via custom fabricated structures.

We were inspired by passive airflow mechanisms in bellows and accordions, which were designed to furnish strong blasts of air without requiring external power. We synthesize similar principles for constructing simple *squeezable units* that can be used for input control. SqueezaPulse is comprised of three core parts: (i) a soft and squeezable cavity to generate airflow; (ii) a tube designed with specific inner-wall corrugations to shape the airflow into unique acoustic signatures, effectively acting as a physical filter [2]; and (iii) a microphone connected to a computer that classifies these signatures for interactive inputs. Figure 2 provides an illustrative example of creating an interactive 3D-printed bunny. Because each tube produces a unique signature, only a single embedded microphone is necessary to sense multiple inputs. To verify

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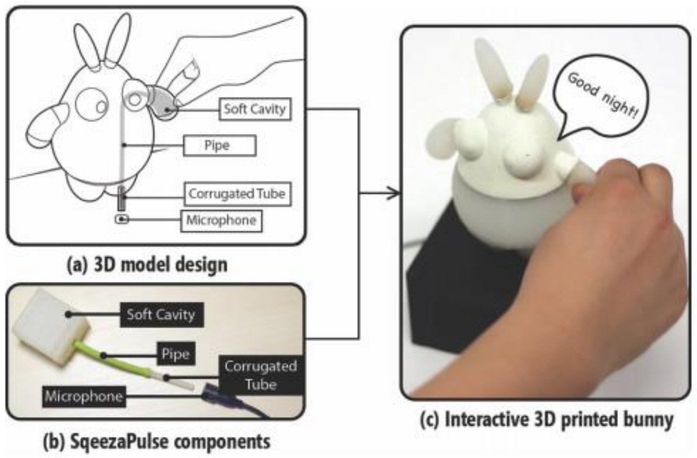

Technique for embedding interactivity into fabricated objects using soft, passive, and low-cost bellow-like structures.

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

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

Journal of Visualized Experiments

Click Here to Watch this Article on JoVE

J Vis Exp. 2011; (58): 3189.
Published online 2011 Dec 9. doi: 10.3791/3189

PMCID: PMC3346051
PMID: 22214978

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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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

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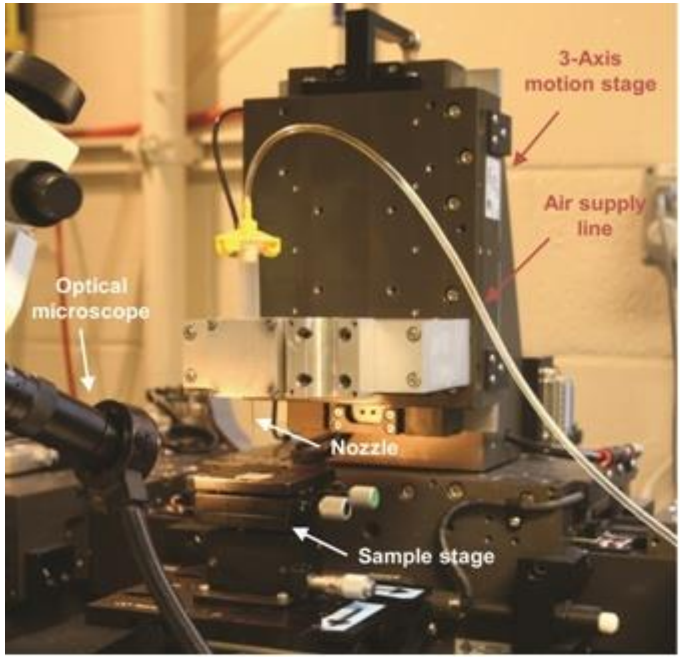
Download video file.(68M, mov)



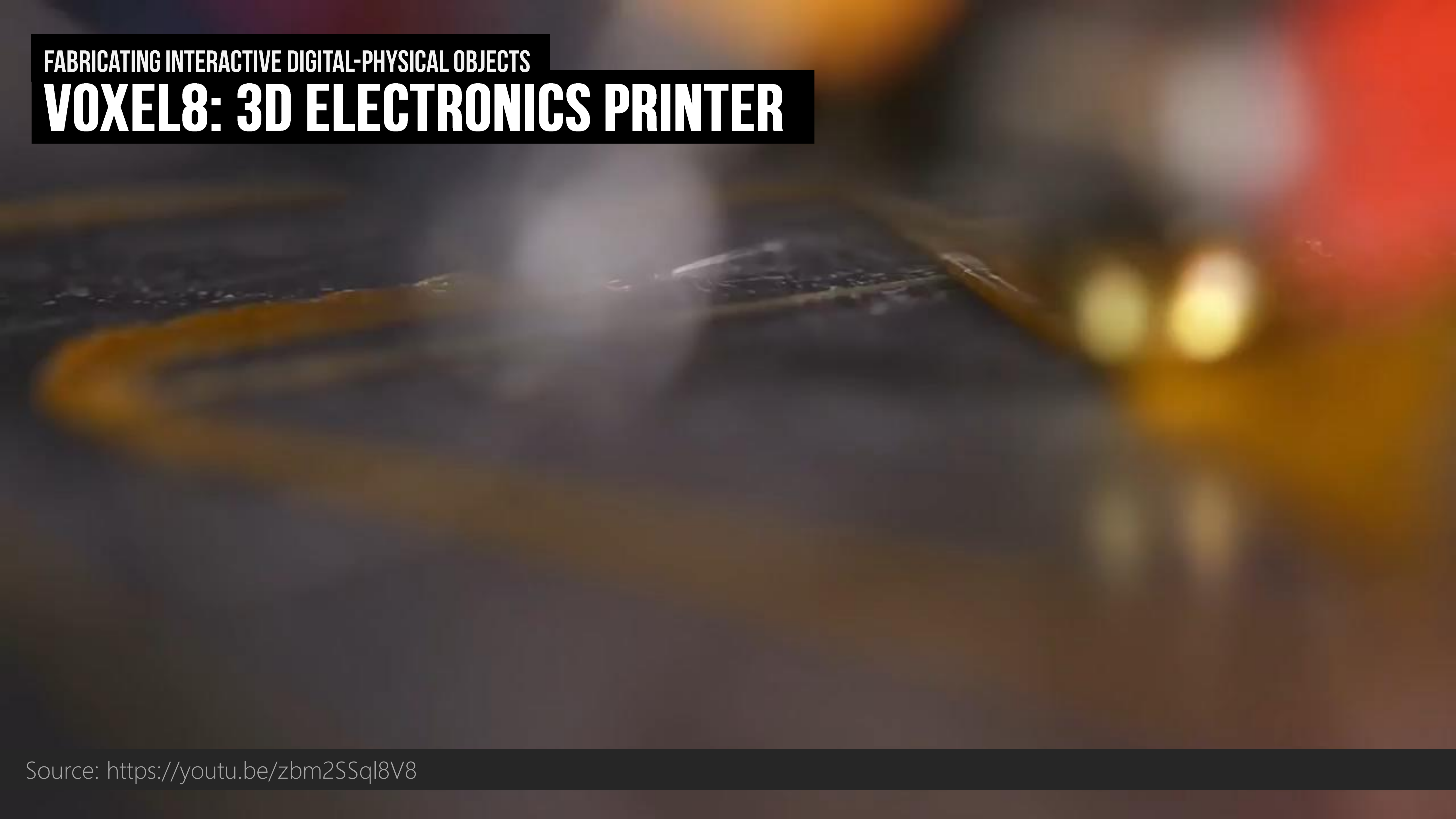
Directly 3D-printing conductive materials is challenging: high-conductivity materials have to be extruded at high temperatures, which melts plastic.

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

Source: Ahn *et al.*, J. of Visualized Experiments 2011

FABRICATING INTERACTIVE DIGITAL-PHYSICAL OBJECTS

VOXEL8: 3D ELECTRONICS PRINTER



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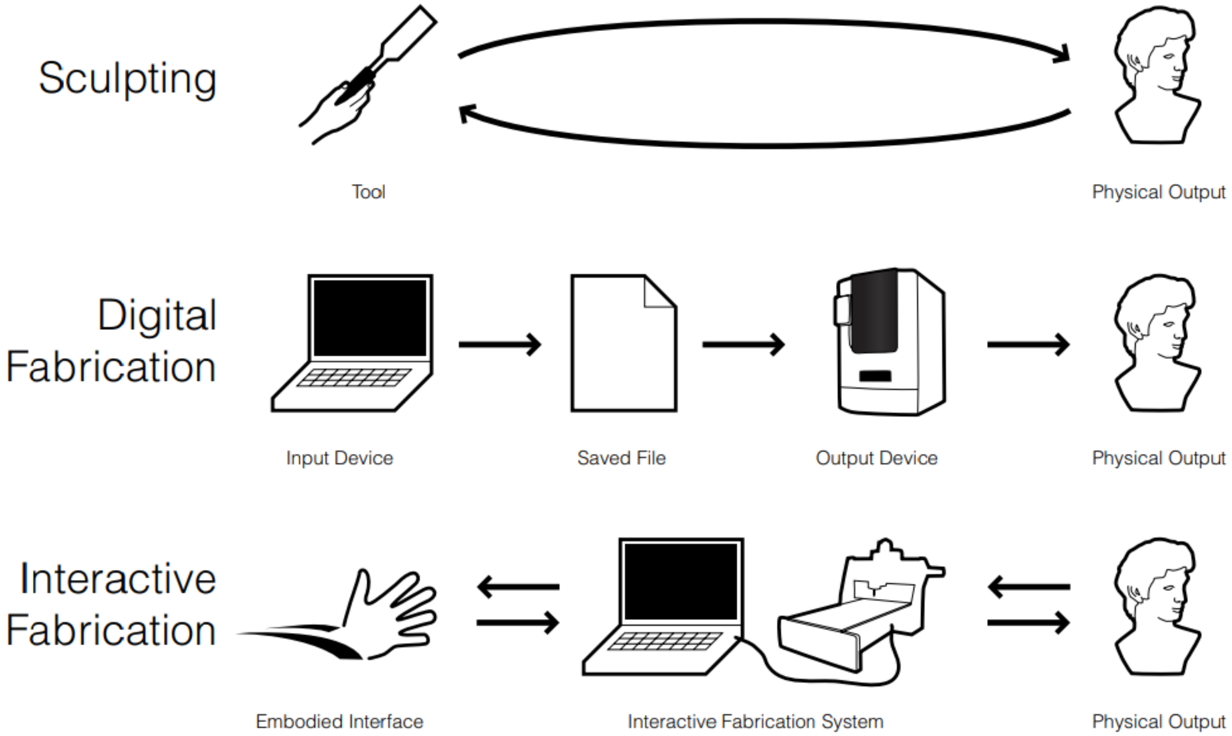
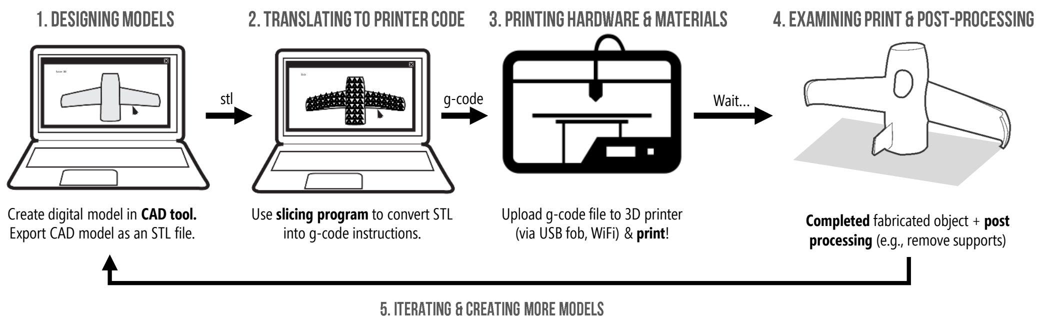
INTERACTIVELY MODELING & FABRICATING



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?

Source: Willis *et al.*, Interactive fabrication: new interfaces for digital fabrication, TEI'10

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

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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 volume. The partially printed physical model then serves 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 printing robotic arm allows the designer to quickly interrupt printing 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-proportioned tangible artifacts 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
H5.2 [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 handcrafting its physical counterpart. On-the-Fly Print [27] combines CAD digital modeling with incremental 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-coiling, but forces the designer to support the entire construction process. On-the-Fly Print produces 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.

Figure 1: a) RoMA overview. b). Designer view from the AR headset. The designer creates a digital spout while the robot prints the teapot body. Digital model is overlaid onto the physical model.

*The two authors contributed equally to this work.

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https://doi.org/10.1145/3173574.3174153

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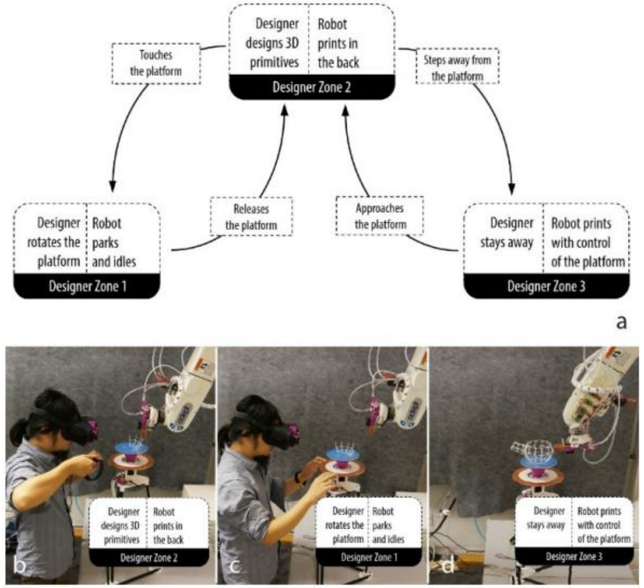


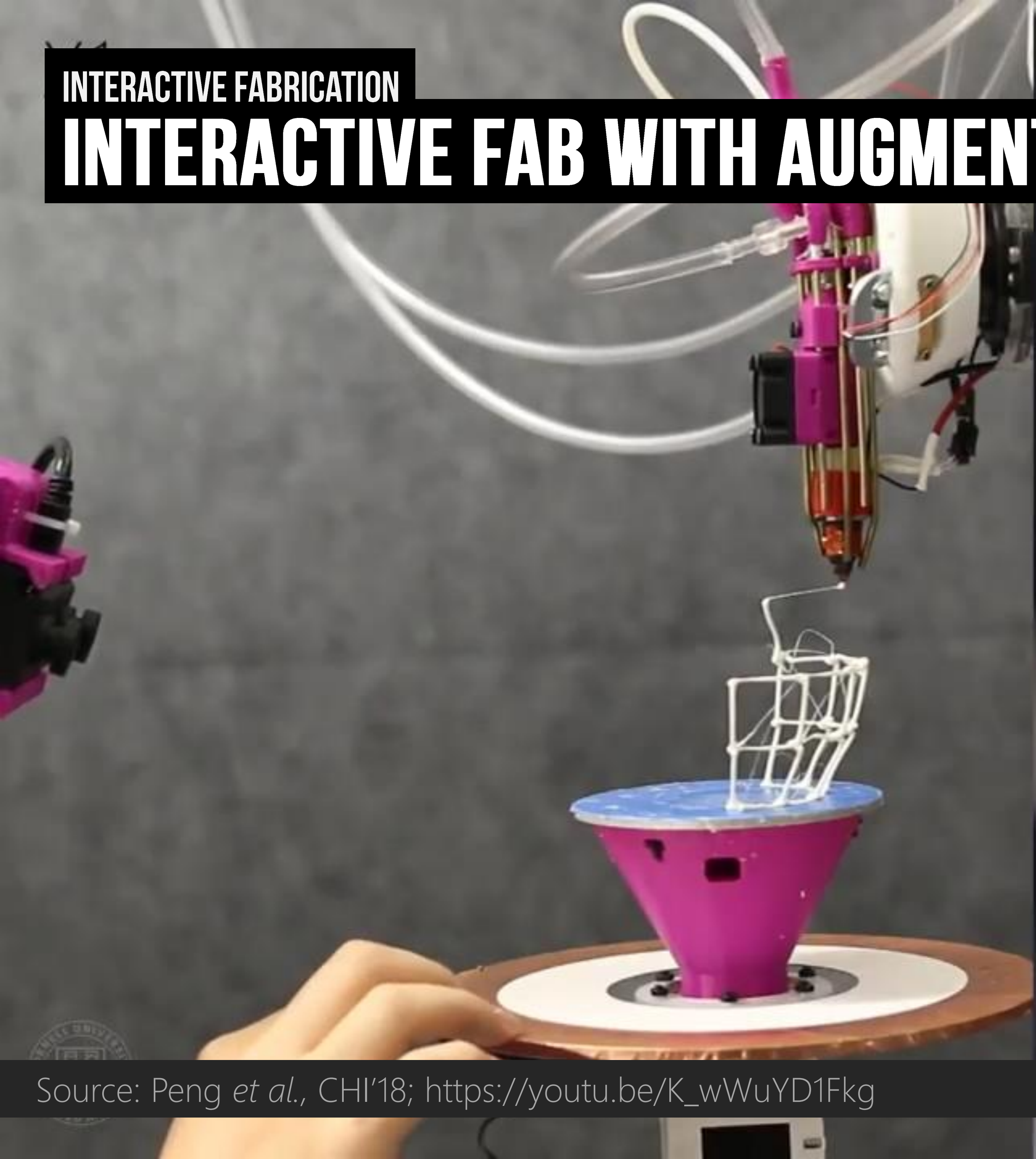
Figure 3. a). Proxemics interaction state machine diagram. Based on different designer zones, the designer can switch among activities such as digital modeling, rotating platform, and complete design; the robot will switch between printing and idle correspondingly. b, c, d). Interaction based on different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

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

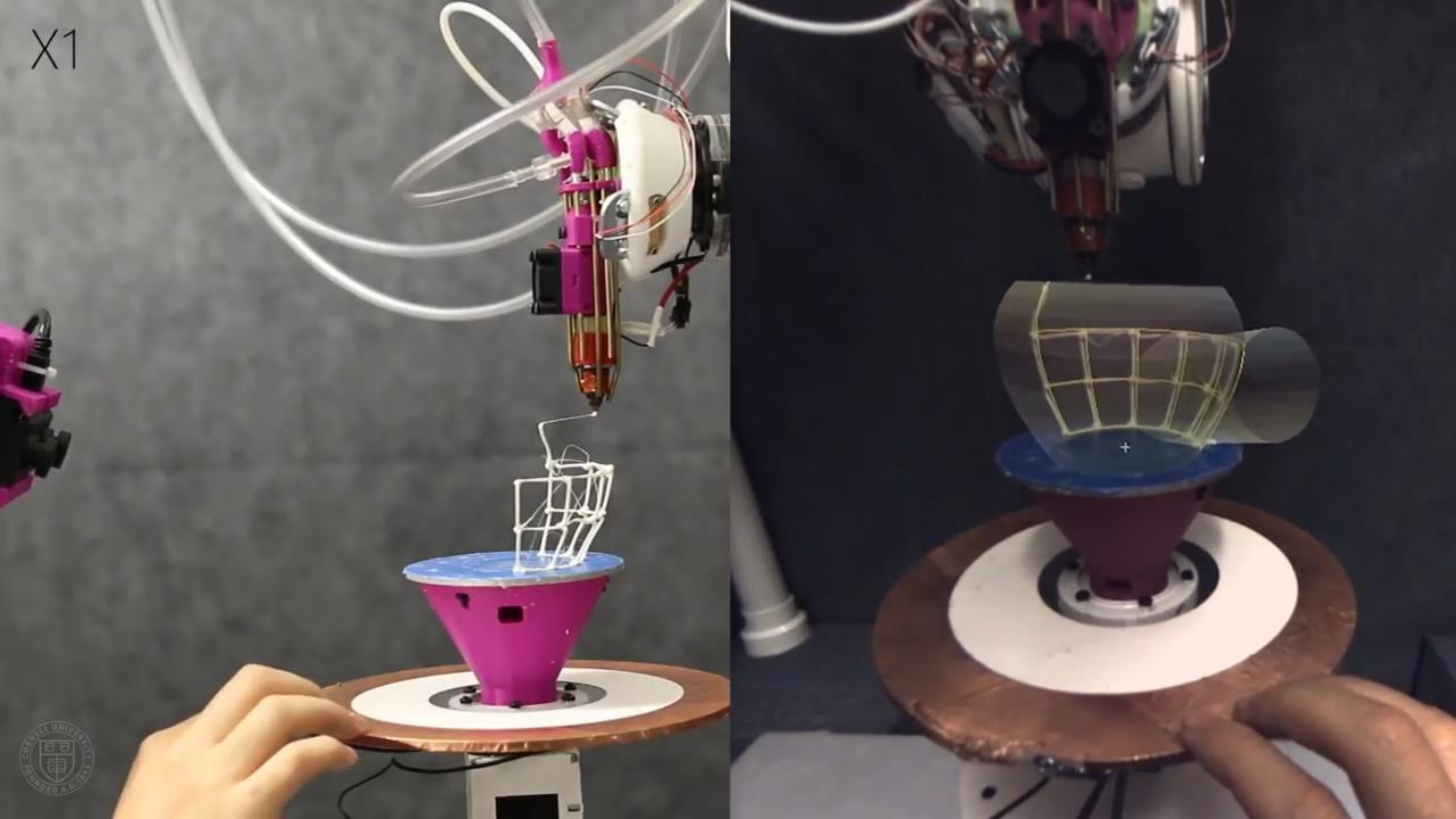
Source: Peng *et al.*, RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer, CHI'18

INTERACTIVE FABRICATION

INTERACTIVE FAB WITH AUGMENTED REALITY



Source: Peng *et al.*, CHI’18; https://youtu.be/K_wWuYD1Fkg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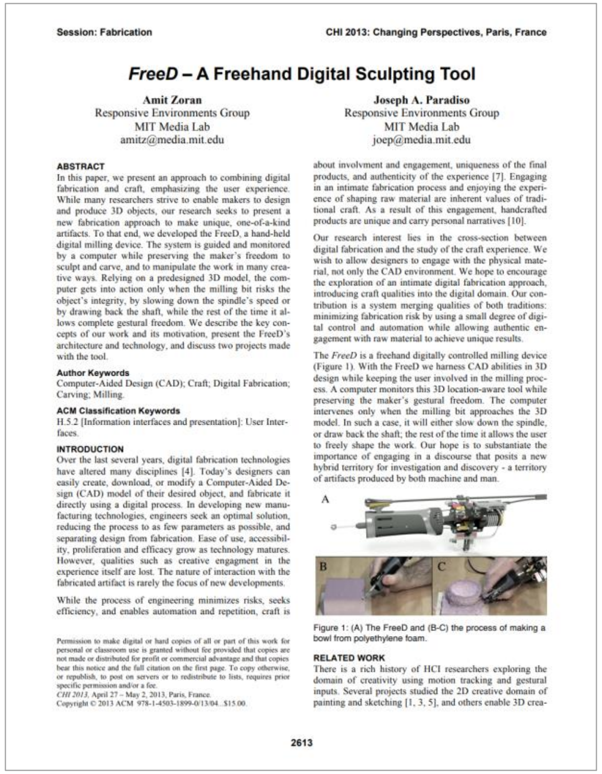
HYBRID COMPUTER-MANUAL CONTROLLED MILLING



FreeD – A Freehand Digital Sculpting Tool

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ABSTRACT
In this paper, we present an approach to combining digital fabrication and craft, emphasizing the user experience. While many researchers strive to enable makers to design and produce 3D objects, our research seeks to present a new fabrication approach to make unique, one-of-a-kind artifacts. To that end, we developed the FreeD, a hand-held digital milling device. The system is guided and monitored by a computer while preserving the maker's freedom to sculpt and carve, and to manipulate the work in many creative ways. Relying on a predesigned 3D model, the computer gets into action only when the milling bit risks the object's integrity, by slowing down the spindle's speed or by drawing back the shaft, while the rest of the time it allows complete gestural freedom. We describe the key concepts of our work and its motivation, present the FreeD's architecture and technology, and discuss two projects made with the tool.

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 altered 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 technologies, engineers seek an optimal solution, reducing the process to as few parameters as possible, and separating design from fabrication. Ease of use, accessibility, proliferation and efficacy grow as technology matures. However, qualities such as creative engagment 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 about involvment and engagement, uniqueness of the final products, and authenticity of the experience [7]. 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 wish to allow designers to engage with the physical material, not only the CAD environment. 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: minimizing fabrication risk by using a small degree of digital control and 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 preserving the maker's gestural freedom. 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 discourse 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-

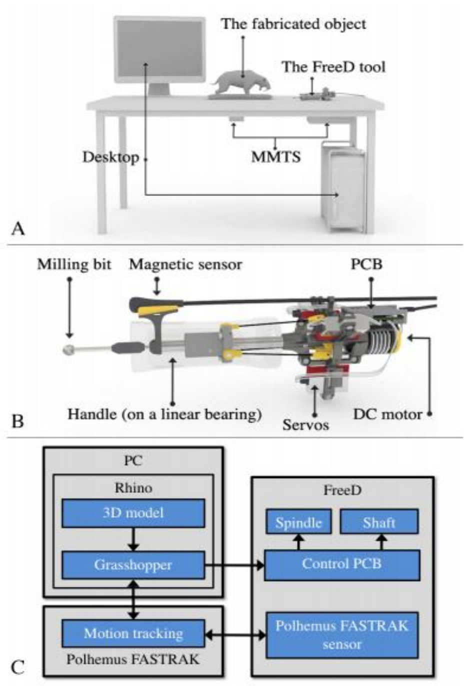


Figure 2: (A) The FreeD's environment, (B) the FreeD design, and (C) the system's data flow.

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."

Source: Zoran & Paradiso, FreeD: a freehand digital sculpting tool, CHI'13

INTERACTIVE FABRICATION

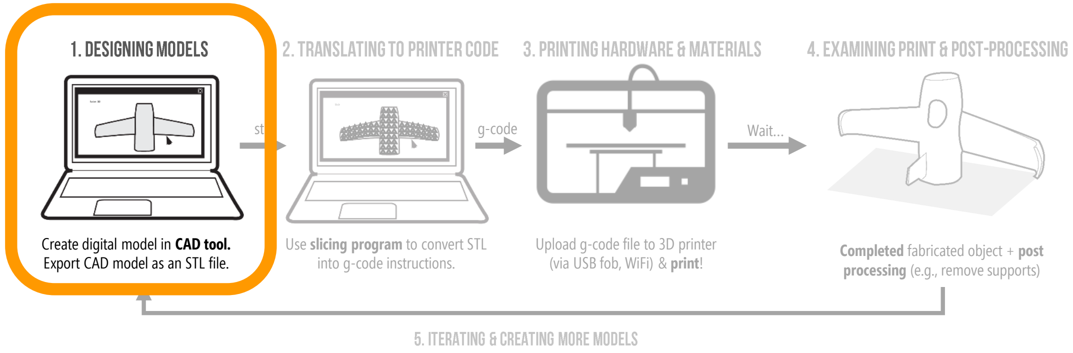
HANDHELD DIGITAL MILLING WITH COMPUTER CONTROL

Source: Zoran *et al.*, CHI’13; https://youtu.be/8NKewmPZbHM

The FreeD

A Handheld Digital Milling Device for Craft & Fabrication

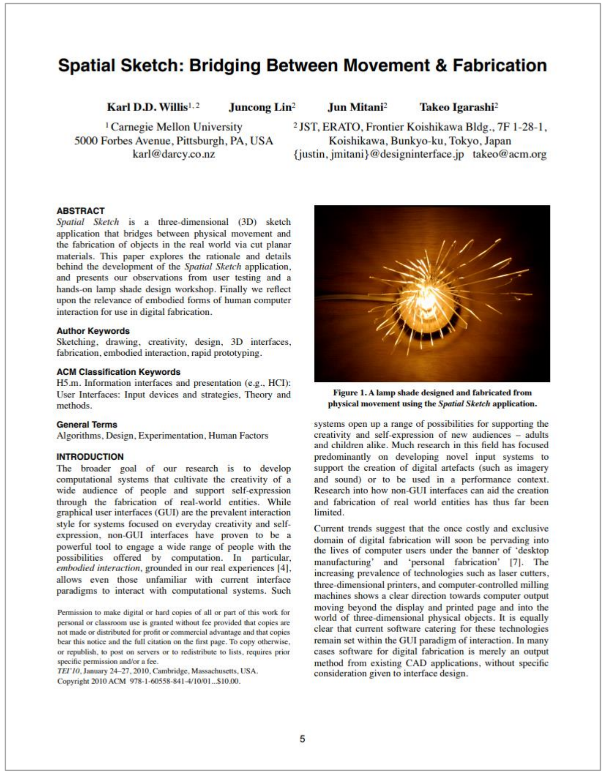
Amit Zoran & Joe Paradiso
Responsive Environment Group



How can we...

Transform the experience of designing CAD models?

RAPIDLY SKETCHING 3D MODELS IN 3D



Spatial Sketch: Bridging Between Movement & Fabrication

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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
H5.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 (GUI) are the prevalent interaction 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 interaction*, grounded in our real experiences [4], allows even those unfamiliar with current interface paradigms to interact with computational systems. Such systems open up a range of possibilities for supporting the creativity and self-expression of new audiences – adults and children alike. Much research in this field has focused predominantly on developing novel input systems to support the creation of digital artefacts (such as imagery and sound) or to be used in a performance context. Research into how non-GUI interfaces can aid the creation and fabrication of real world entities has thus far been limited.

Current trends suggest that the once costly and exclusive domain of digital fabrication will soon be pervading into the lives of computer users under the banner of 'desktop manufacturing' and 'personal fabrication' [7]. The increasing prevalence of technologies such as laser cutters, three-dimensional printers, and computer-controlled milling machines shows a clear direction towards computer output moving beyond the display and printed page and into the world of three-dimensional physical objects. It is equally clear that current software catering for these technologies remain set within the GUI paradigm of interaction. In many cases software for digital fabrication is merely an output method from existing CAD applications, without specific consideration given to interface design.

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

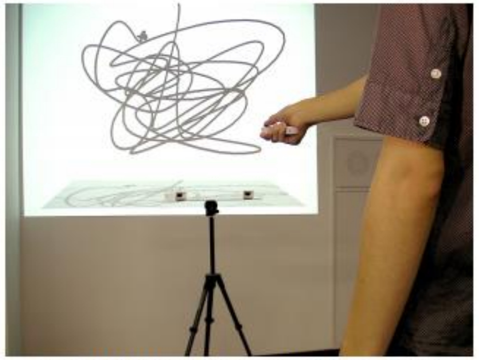


Figure 2. Sketching with the *Spatial Sketch* application.

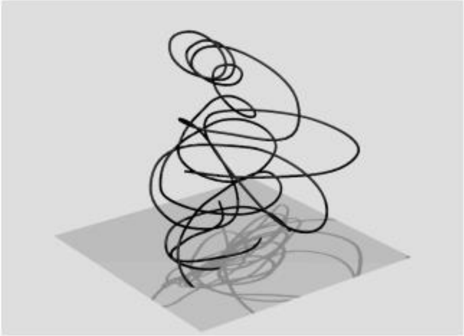


Figure 3. A sketch created using the *Spatial Sketch* 3D input system with line smoothing applied in real-time.

Invites us to rethink approaches to CAD modeling.

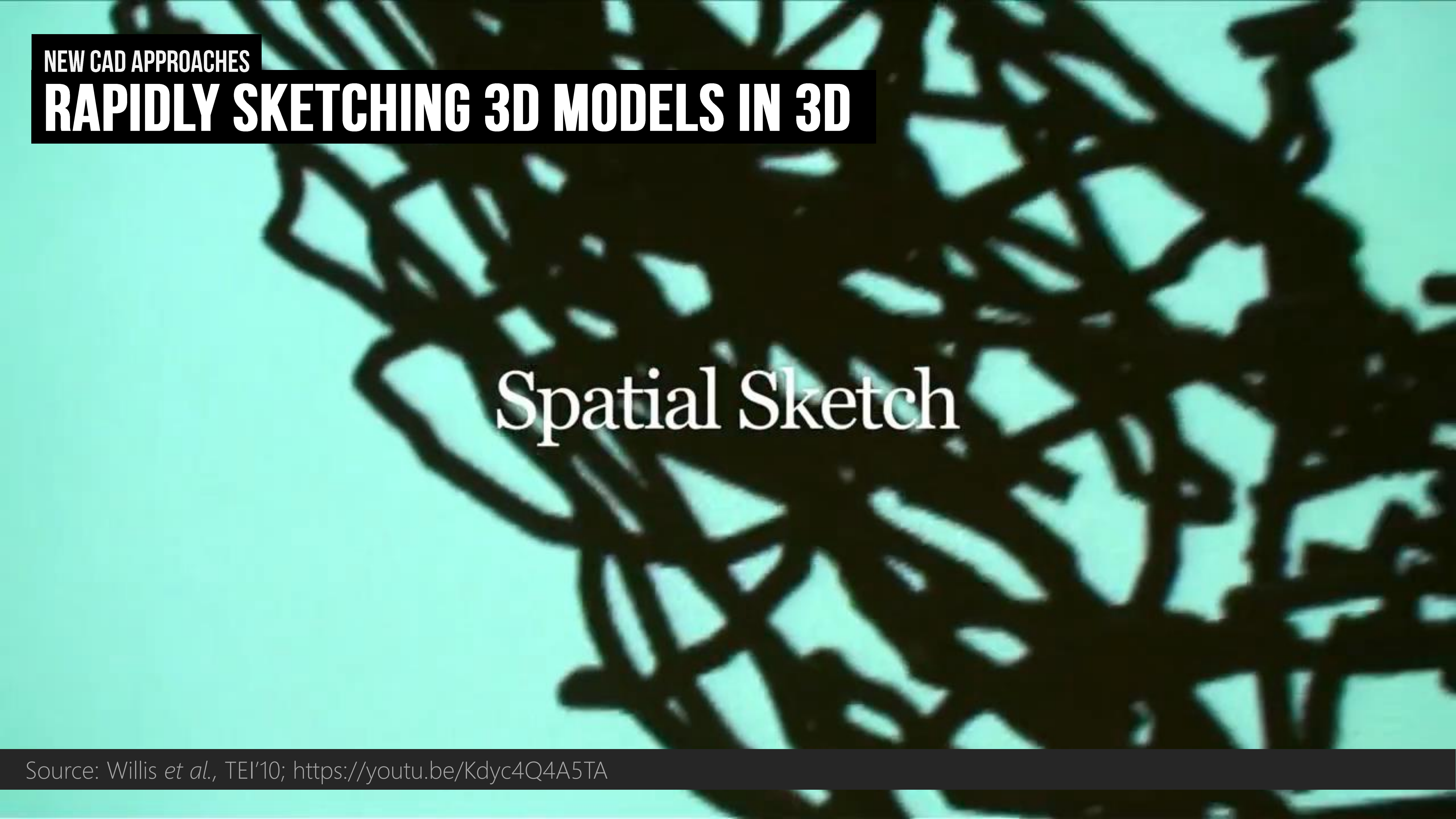
Presents a 3D sketching tool that is controlled by arm movement.

Validates approach via a design workshop with children

Source: Zoran & Paradiso, FreeD: a freehand digital sculpting tool, CHI'13

NEW CAD APPROACHES

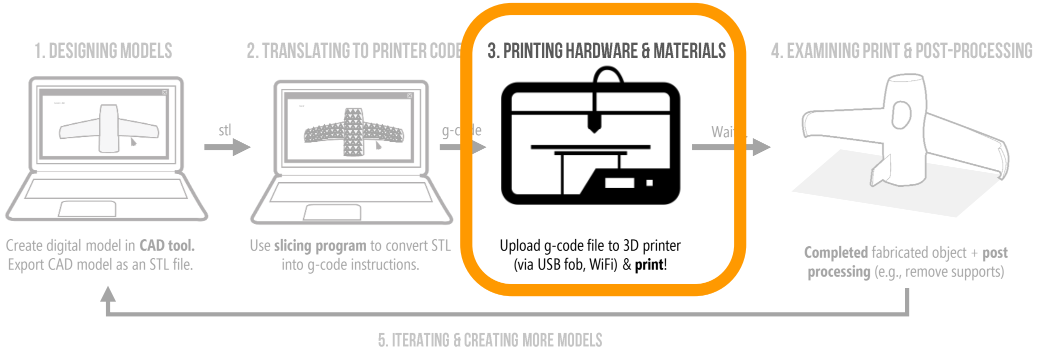
RAPIDLY SKETCHING 3D MODELS IN 3D



Source: Willis *et al.*, TEI’10; https://youtu.be/Kdyc4Q4A5TA


Spatial Sketch

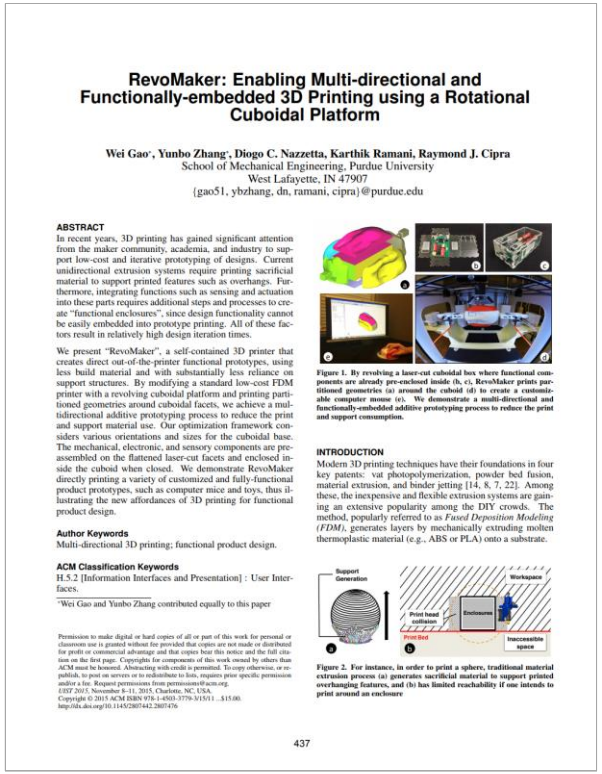
HOW CAN WE IMPROVE FDM HARDWARE?



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

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ABSTRACT

In recent years, 3D printing has gained significant attention from the maker community, academia, and industry to support low-cost and iterative prototyping of designs. Current unidirectional extrusion systems require printing sacrificial material to support printed features such as overhangs. Furthermore, integrating functions such as sensing and actuation into these parts requires additional steps and processes to create "functional enclosures", since design functionality cannot be easily embedded into prototype printing. 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-printer functional prototypes, using less build material and with substantially less reliance on support structures. By modifying a standard low-cost FDM printer with a revolving cuboidal platform and printing partitioned geometries around cuboidal facets, we achieve a multidirectional additive prototyping process to reduce the print and support material use. Our optimization framework considers various orientations and sizes for the cuboidal base. The mechanical, electronic, and sensory components are preassembled on the flattened laser-cut facets and enclosed inside the cuboid when closed. We demonstrate RevoMaker directly printing a 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

Figure 1. By revolving a laser-cut cuboidal box where functional components are already pre-enclosed inside (b, c), RevoMaker prints partitioned geometries (a) around the cuboid (d) to create a customizable computer mouse (e). We demonstrate a multi-directional and functionally-embedded additive prototyping process to reduce the print and support consumption.

INTRODUCTION

Modern 3D printing techniques have their foundations in four key patents: vat photopolymerization, powder bed fusion, material extrusion, and binder jetting [14, 8, 7, 22]. Among these, the inexpensive and flexible extrusion systems are gaining an extensive popularity among the DIY crowds. The method, popularly referred to as *Fused Deposition Modeling (FDM)*, generates layers by mechanically extruding molten thermoplastic material (e.g., ABS or PLA) onto a substrate.

Figure 2. For instance, in order to print a sphere, traditional material extrusion process (a) generates sacrificial material to support printed overhanging features, and (b) has limited reachability if one intends to print around an enclosure

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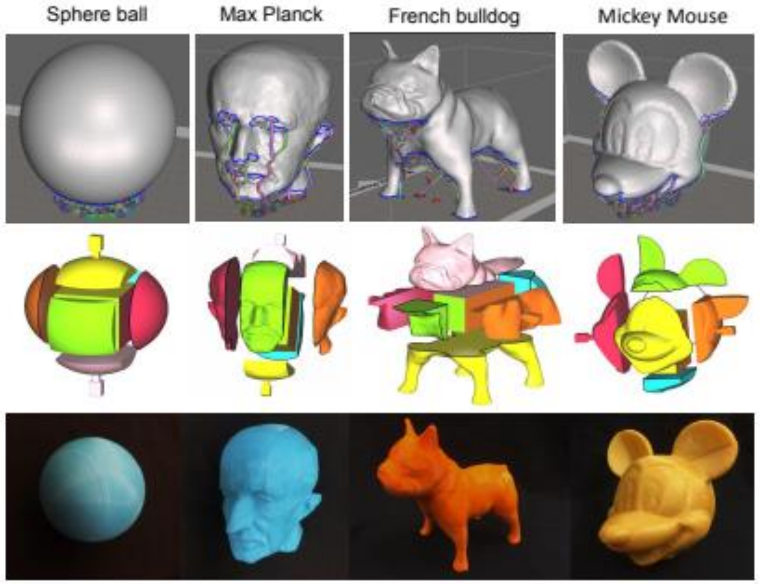


Figure 10. first row: visualization of support generation for a sphere ball, Max Planck, French bulldog and Mickey Mouse head using existing FDM printing process in Ultimaker2 (the model is oriented where less support structures are created. second row: partitioned results of each model. third row: prototypical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

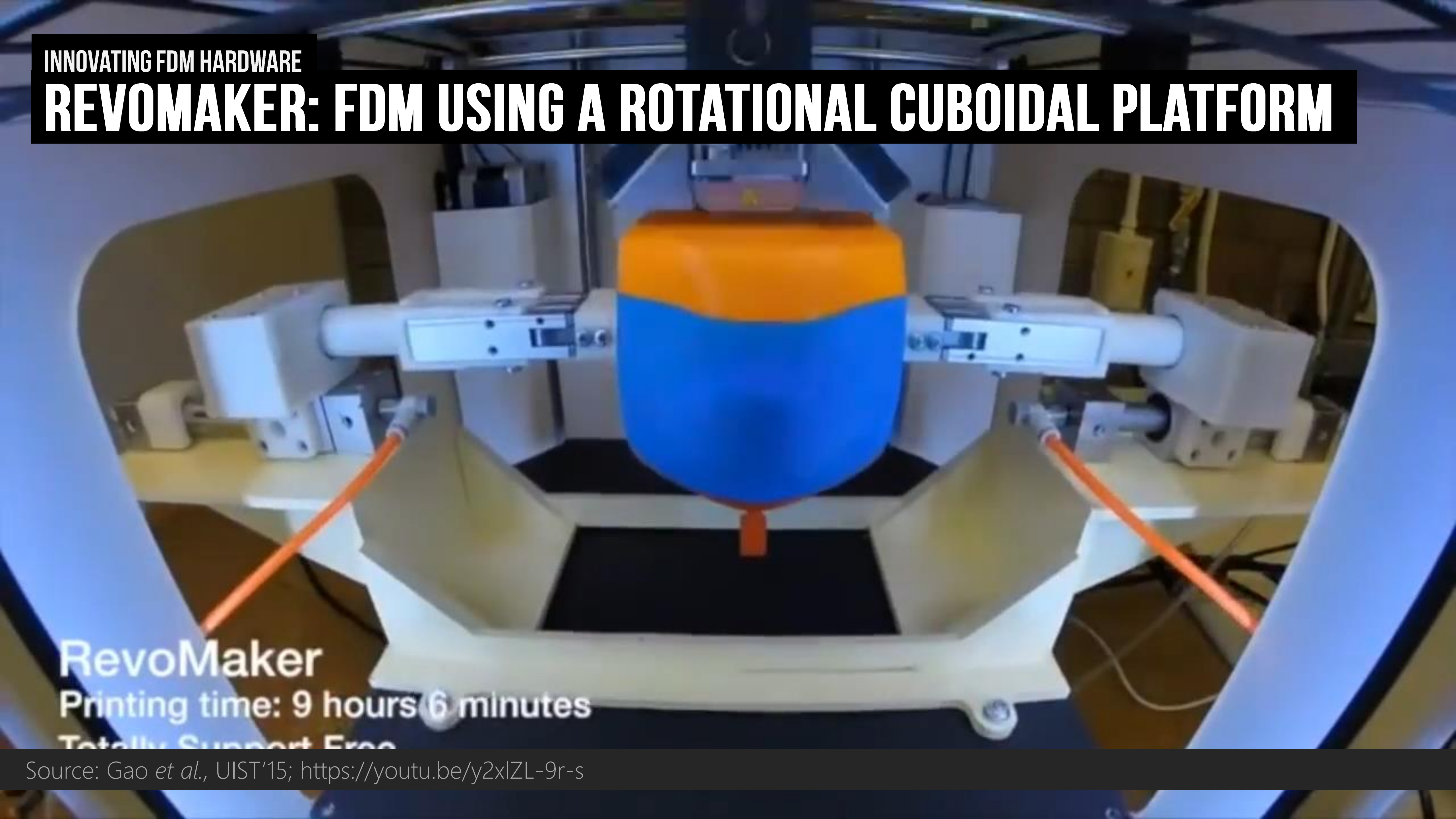
Table 1. Comparison of time and total material reduction using RevoMaker and Ultimaker 2.

Models	RevoMaker		Ultimaker 2				time reduction	total material reduction
	total time (hh:mm)	build volume (cm^3)	time (hh:mm)		build volume (cm^3)		compared to t_{min}	compared to V_{min}
			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%

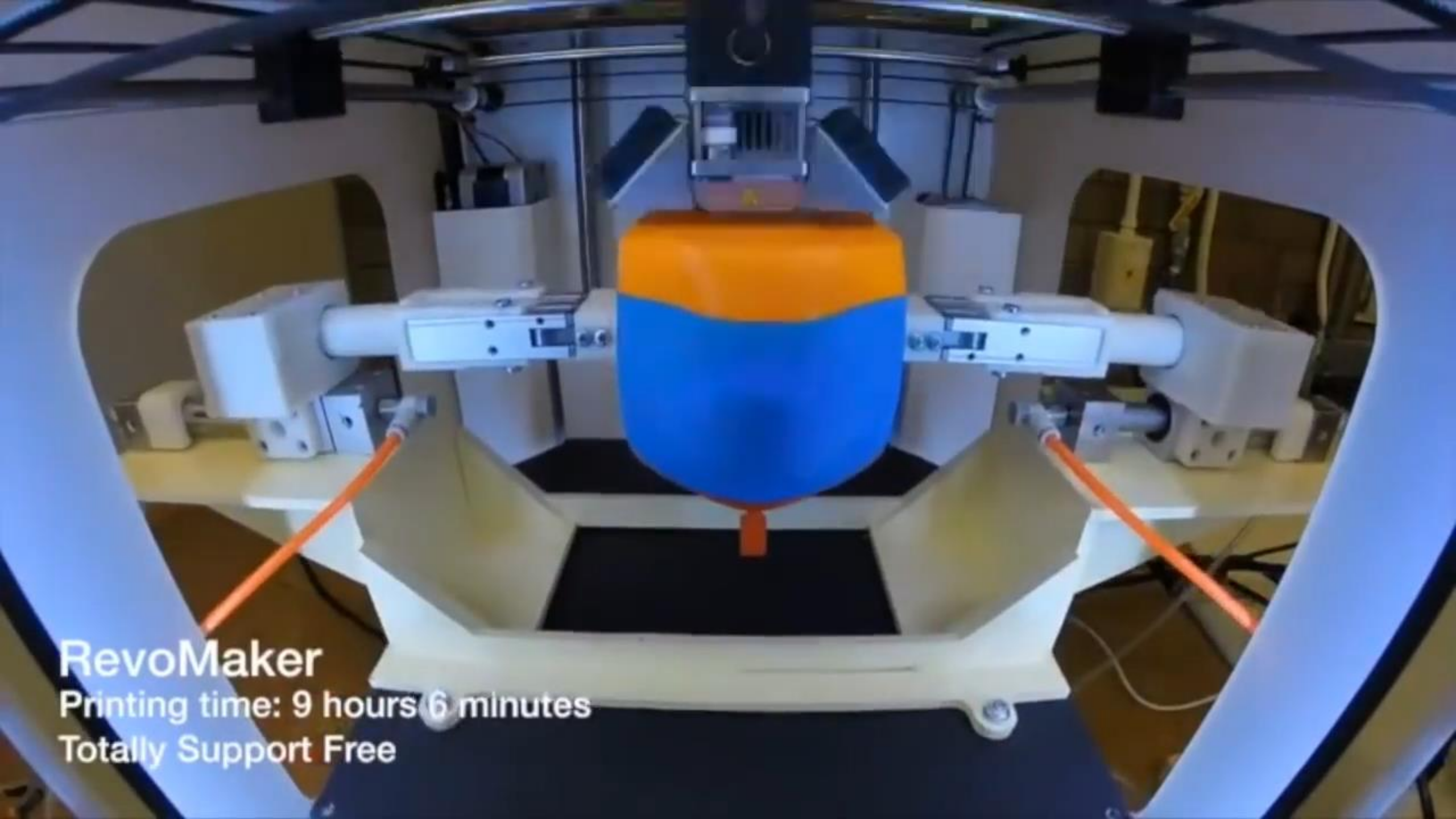
*By placing a model in different orientations, t_{min} and t_{max} are the minimum and maximum time duration using Ultimaker 2; V_{min} and V_{max} are the minimum and maximum consumption of overall material (build + support), $V_{support}$ is only the consumption of support material. Using RevoMaker, 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.

Source: Gao *et al.*, RevoMaker: Enabling Multi-directional and Functionally-embedded 3D printing using a Rotational Cuboidal Platform, UIST'15

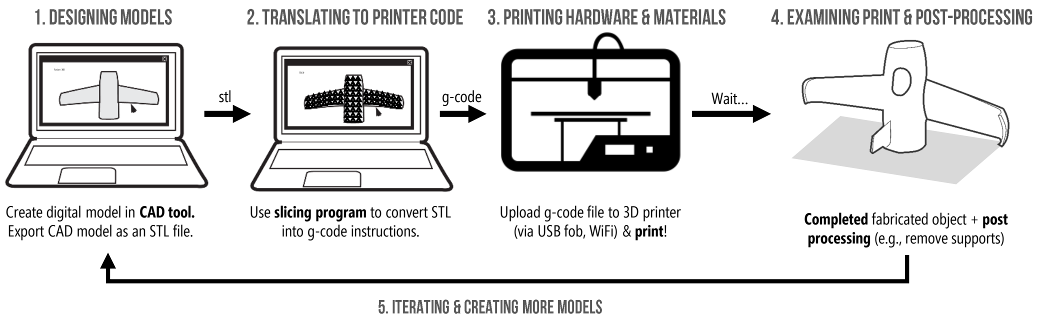
REVOMAKER: FDM USING A ROTATIONAL CUBOIDAL PLATFORM



Source: Gao *et al.*, UIST’15; https://youtu.be/y2xlZL-9r-s


RevoMaker
Printing time: 9 hours 6 minutes
Totally Support Free

HOW TO IMPROVE ROBUSTNESS

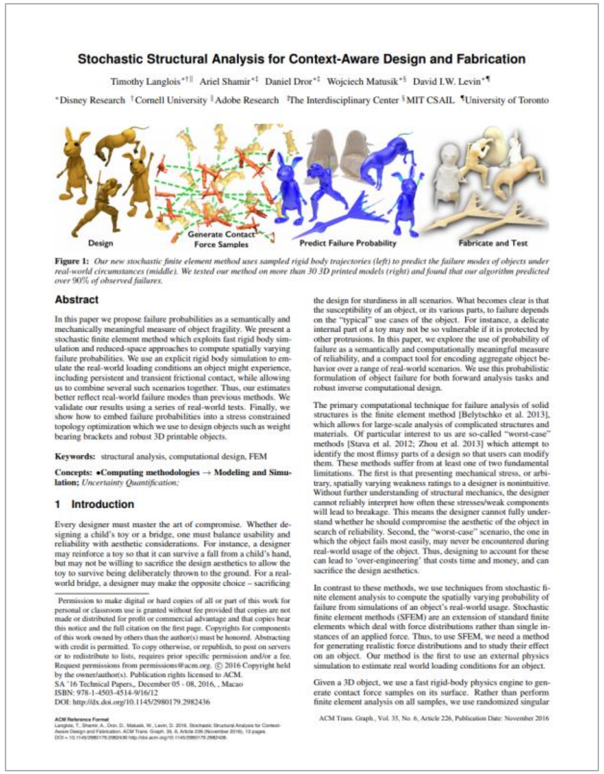


How can we…

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

IMPROVING ROBUSTNESS

STOCHASTIC STRUCTURAL ANALYSIS



Stochastic Structural Analysis for Context-Aware Design and Fabrication

Timothy Langlois[*,†,‖] Ariel Shamir[*,‡] Daniel Dror[*,‡] Wojciech Matusik[*,§] David I.W. Levin[*,¶]

[*]Disney Research [†]Cornell University [‖]Adobe Research [‡]The Interdisciplinary Center [§]MIT CSAIL [¶]University of Toronto

Figure 1: *Our new stochastic finite element method uses sampled rigid body trajectories (left) to predict the failure modes of objects under real-world circumstances (middle). We tested our method on more than 30 3D printed models (right) and found that our algorithm predicted over 90% of observed failures.*

Abstract

In this paper we propose failure probabilities as a semantically and mechanically meaningful measure of object fragility. We present a stochastic finite element method which exploits fast rigid body simulation and reduced-space approaches to compute spatially varying failure probabilities. We use an explicit rigid body simulation to emulate the real-world loading conditions an object might experience, including persistent and transient frictional contact, while allowing us to combine several such scenarios together. Thus, our estimates better reflect real-world failure modes than previous methods. We validate our results using a series of real-world tests. Finally, we show how to embed failure probabilities into a stress constrained topology optimization which we use to design objects such as weight bearing brackets and robust 3D printable objects.

Keywords: structural analysis, computational design, FEM

Concepts: •**Computing methodologies** → **Modeling and Simulation;** *Uncertainty Quantification;*

1 Introduction

Every designer must master the art of compromise. Whether designing a child's toy or a bridge, one must balance usability and reliability with aesthetic considerations. For instance, a designer may reinforce a toy so that it can survive a fall from a child's hand, but may not be willing to sacrifice the design aesthetics to allow the toy to survive being deliberately thrown to the ground. For a real-world bridge, a designer may make the opposite choice – sacrificing the design for sturdiness in all scenarios. What becomes clear is that the susceptibility of an object, or its various parts, to failure depends on the "typical" use cases of the object. For instance, a delicate internal part of a toy may not be so vulnerable if it is protected by other protrusions. In this paper, we explore the use of probability of failure as a semantically and computationally meaningful measure of reliability, and a compact tool for encoding aggregate object behavior over a range of real-world scenarios. We use this probabilistic formulation of object failure for both forward analysis tasks and robust inverse computational design.

The primary computational technique for failure analysis of solid structures is the finite element method [Belytschko et al. 2013], which allows for large-scale analysis of complicated structures and materials. Of particular interest to us are so-called "worst-case" methods [Stava et al. 2012; Zhou et al. 2013] which attempt to identify the most flimsy parts of a design so that users can modify them. These methods suffer from at least one of two fundamental limitations. The first is that presenting mechanical stress, or arbitrary, spatially varying weakness ratings to a designer is nonintuitive. Without further understanding of structural mechanics, the designer cannot reliably interpret how often these stresses/weak components will lead to breakage. This means the designer cannot fully understand whether he should compromise the aesthetic of the object in search of reliability. Second, the "worst-case" scenario, the one in which the object fails most easily, may never be encountered during real-world usage of the object. Thus, designing to account for these can lead to 'over-engineering' that costs time and money, and can sacrifice the design aesthetics.

In contrast to these methods, we use techniques from stochastic finite element analysis to compute the spatially varying probability of failure from simulations of an object's real-world usage. Stochastic finite element methods (SFEM) are an extension of standard finite elements which deal with force distributions rather than single instances of an applied force. Thus, to use SFEM, we need a method for generating realistic force distributions and to study their effect on an object. Our method is the first to use an external physics simulation to estimate real world loading conditions for an object.

Given a 3D object, we use a fast rigid-body physics engine to generate contact force samples on its surface. Rather than perform finite element analysis on all samples, we use randomized singular

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DOI: http://dx.doi.org/10.1145/2980179.2982436

ACM Reference Format
Langlois, T., Shamir, A., Dror, D., Matusik, W., Levin, D. 2016. Stochastic Structural Analysis for Context-Aware Design and Fabrication. ACM Trans. Graph. 35, 6, Article 226 (November 2016), 13 pages.

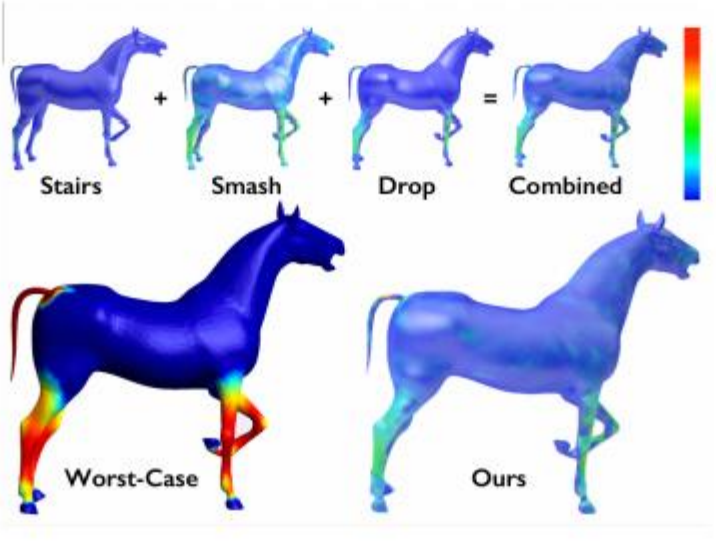


Figure 7: *Top: Our method supports seamlessly combining samples from multiple scenarios to provide an aggregate analysis. Bottom: We compare our combined results to the worst-case analysis for the same pose. Worst-case both fails to predict the non-fragile legs in the stairs and drop cases as well as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

Improves upon traditional finite element analyses with a stochastic model

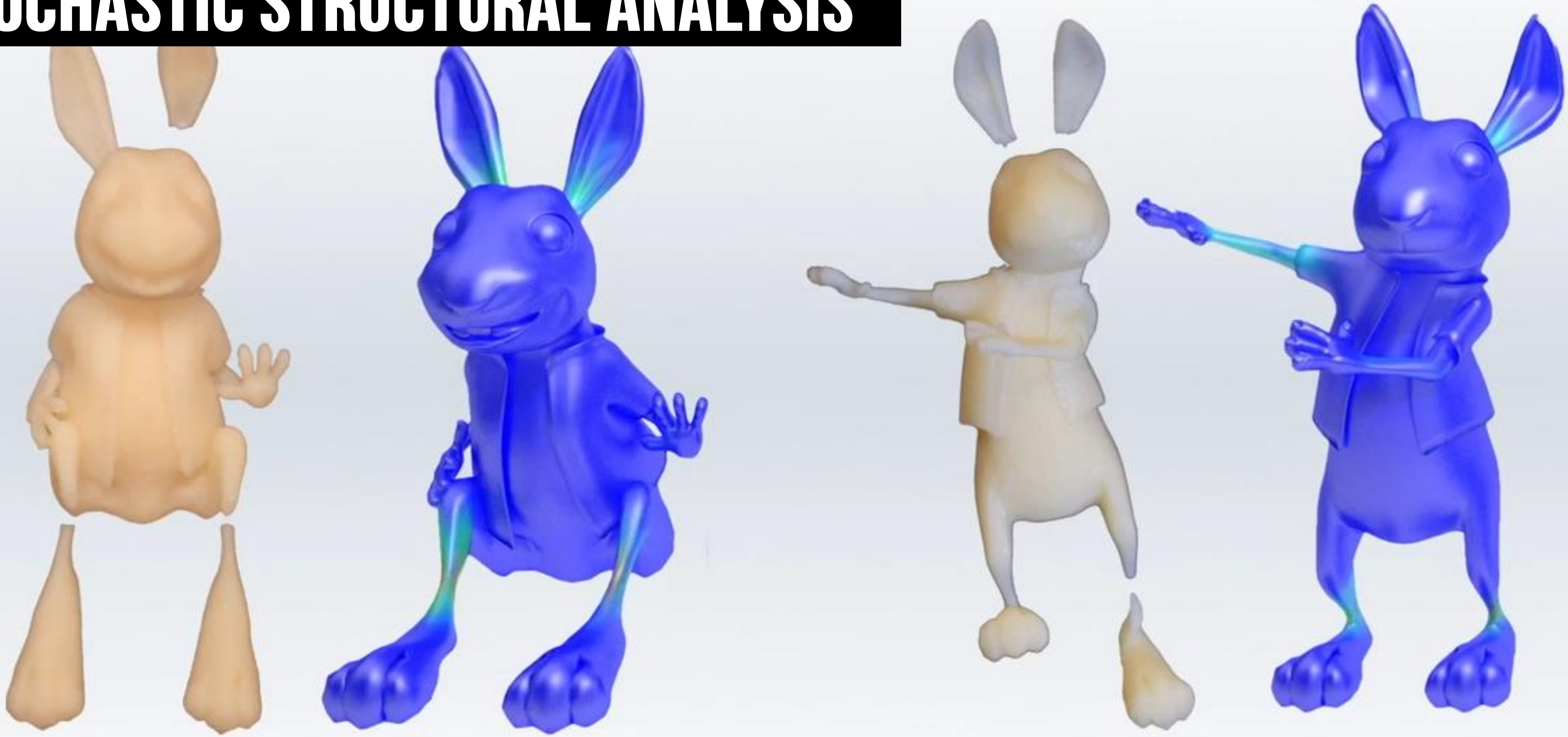
Identifies more accurate failure probabilities than status quo

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

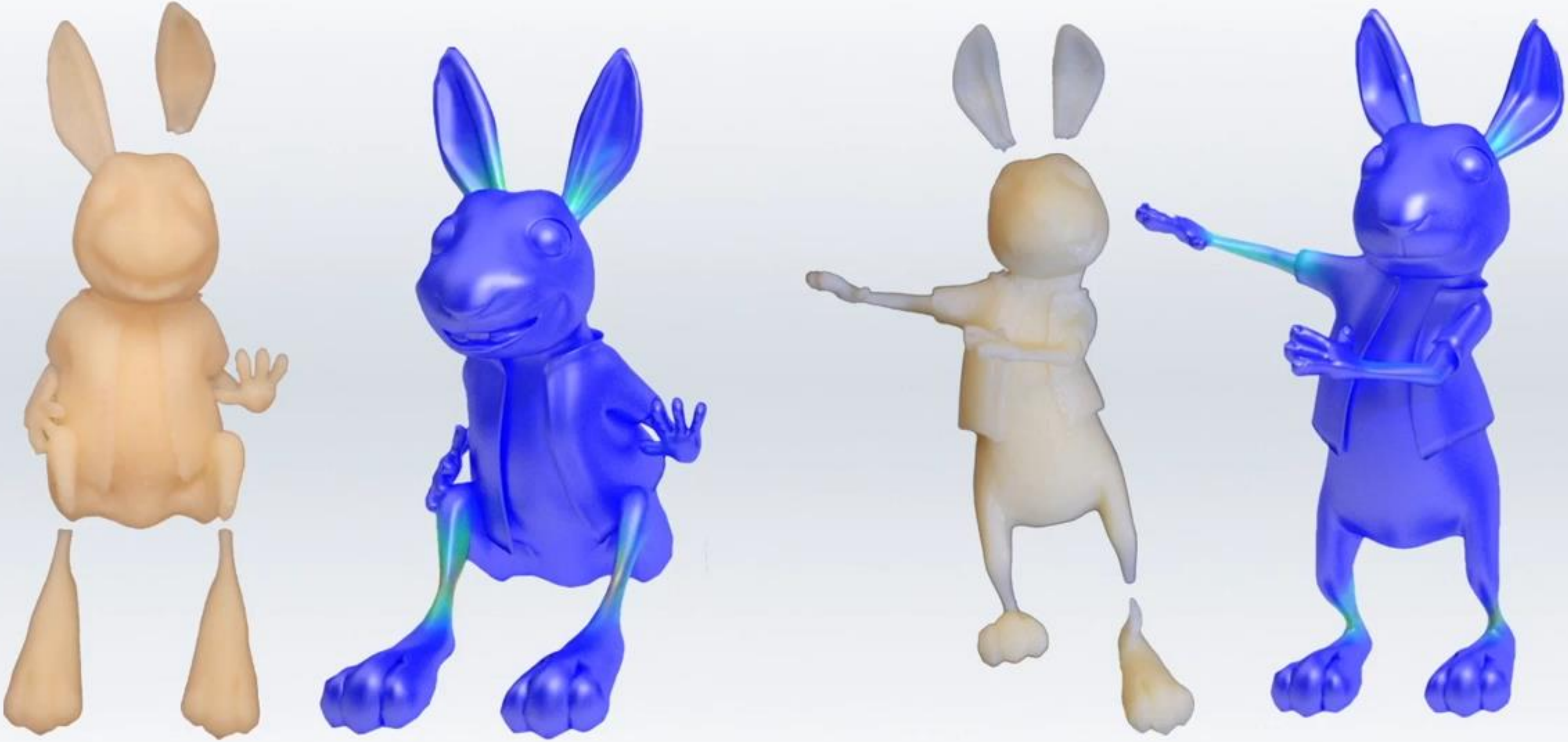
Source: Langlois *et al.*, Stochastic structural analysis for context-aware design and fabrication, ACM Trans. Graphics'16

IMPROVING ROBUSTNESS

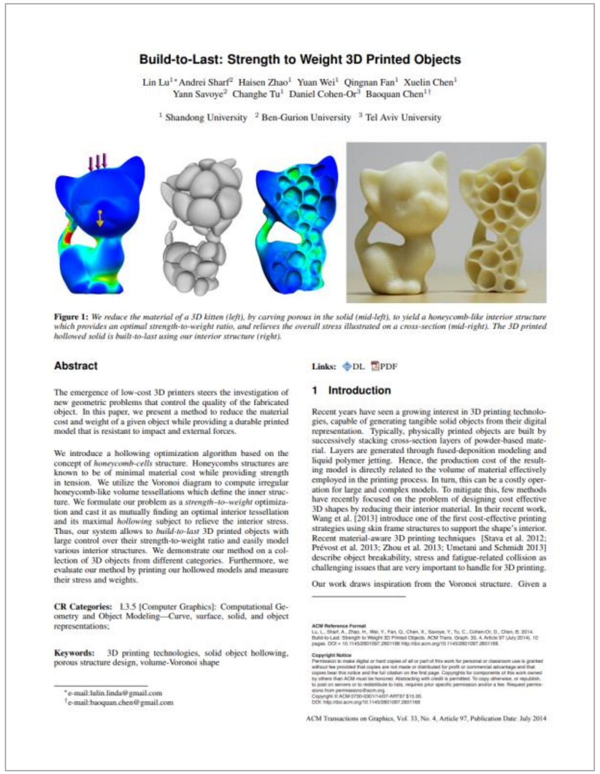
STOCHASTIC STRUCTURAL ANALYSIS



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



OPTIMIZING INFILL TO REDUCE WEIGHT BUT MAINTAIN DURABILITY



Build-to-Last: Strength to Weight 3D Printed Objects

Lin Lu[1]* Andrei Sharf[2] Haisen Zhao[1] Yuan Wei[1] Qingnan Fan[1] Xuelin Chen[1]
Yann Savoye[2] Changhe Tu[1] Daniel Cohen-Or[3] Baoquan Chen[1]†

[1] Shandong University [2] Ben-Gurion University [3] Tel Aviv University

Figure 1: *We reduce the material of a 3D kitten (left), by carving porous in the solid (mid-left), to yield a honeycomb-like interior structure which provides an optimal strength-to-weight ratio, and relieves the overall stress illustrated on a cross-section (mid-right). The 3D printed hollowed solid is built-to-last using our interior structure (right).*

Abstract

The emergence of low-cost 3D printers steers the investigation of new geometric problems that control the quality of the fabricated object. In this paper, we present a method to reduce the material cost and weight of a given object while providing a durable printed model that is resistant to impact and external forces.

We introduce a hollowing optimization algorithm based on the concept of *honeycomb-cells* structure. Honeycombs structures are known to be of minimal material cost while providing strength in tension. We utilize the Voronoi diagram to compute irregular honeycomb-like volume tessellations which define the inner structure. We formulate our problem as a *strength–to–weight* optimization and cast it as mutually finding an optimal interior tessellation and its maximal *hollowing* subject to relieve the interior stress. Thus, our system allows to *build-to-last* 3D printed objects with large control over their strength-to-weight ratio and easily model various interior structures. We demonstrate our method on a collection of 3D objects from different categories. Furthermore, we evaluate our method by printing our hollowed models and measure their stress and weights.

CR Categories: I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations;

Keywords: 3D printing technologies, solid object hollowing, porous structure design, volume-Voronoi shape

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Links: DL PDF

1 Introduction

Recent years have seen a growing interest in 3D printing technologies, capable of generating tangible solid objects from their digital representation. Typically, physically printed objects are built by successively stacking cross-section layers of powder-based material. Layers are generated through fused-deposition modeling and liquid polymer jetting. Hence, the production cost of the resulting model is directly related to the volume of material effectively employed in the printing process. In turn, this can be a costly operation for large and complex models. To mitigate this, few methods have recently focused on the problem of designing cost effective 3D shapes by reducing their interior material. In their recent work, Wang et al. [2013] introduce one of the first cost-effective printing strategies using skin frame structures to support the shape's interior. Recent material-aware 3D printing techniques [Stava et al. 2012; Prévost et al. 2013; Zhou et al. 2013; Umetani and Schmidt 2013] describe object breakability, stress and fatigue-related collision as challenging issues that are very important to handle for 3D printing.

Our work draws inspiration from the Voronoi structure. Given a

ACM Reference Format
Lu, L., Sharf, A., Zhao, H., Wei, Y., Fan, Q., Chen, X., Savoye, Y., Tu, C., Cohen-Or, D., Chen, B. 2014. Build-to-Last: Strength to Weight 3D Printed Objects. ACM Trans. Graph. 33, 4, Article 97 (July 2014), 10 pages. DOI = 10.1145/2601097.2601168 http://doi.acm.org/10.1145/2601097.2601168.

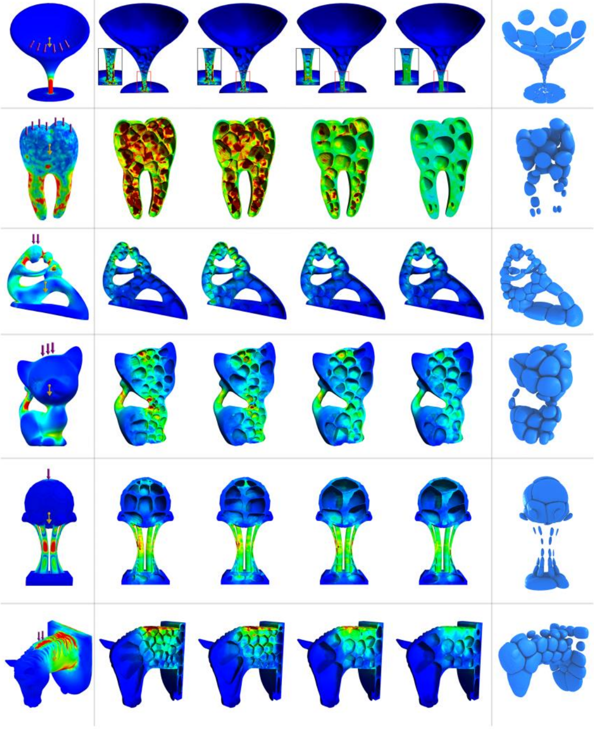


Figure 13: *Build-to-last hollowing results for six different models. Left-to-right, original model with applied forces and initial stress map, three optimization iterations, our optimal strength-to-weight result and rightmost are the resulting 3D porous.*

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

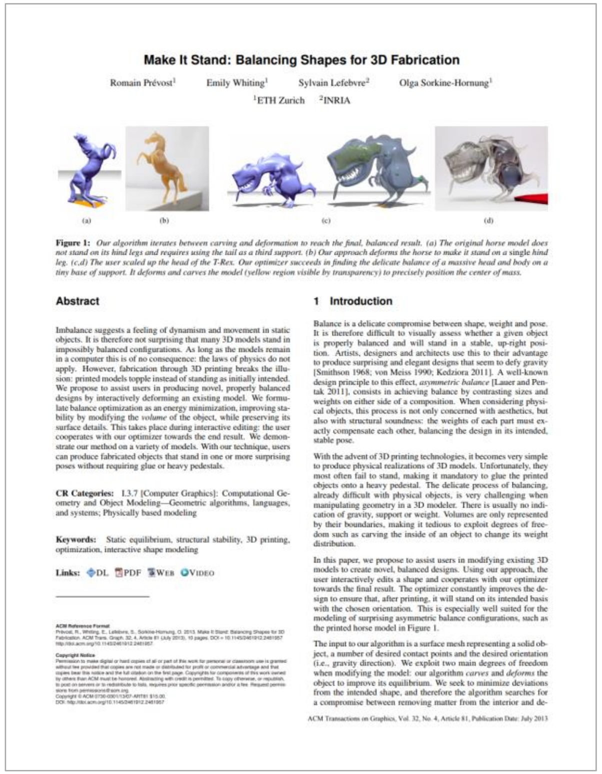
Validates method empirically using mechanical stress testing

Source: Lu *et al.*, Build-to-last: strength to weight 3D printed objects. ACM Trans. Graph'14

OPTIMIZING INFILL TO REDUCE WEIGHT BUT MAINTAIN DURABILITY

Source: Lu *et al.*, ACM Trans. Graph.'14; https://youtu.be/V5IrPSvcm_8

MODIFYING INFILL & SHAPE TO IMPROVE OBJECT BALANCE



Make It Stand: Balancing Shapes for 3D Fabrication

Romain Prévost[1] Emily Whiting[1] Sylvain Lefebvre[2] Olga Sorkine-Hornung[1]

[1]ETH Zurich [2]INRIA

(a) (b) (c) (d)

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 scaled 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 dynamism 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 this is of no consequence: the laws of physics do not apply. However, fabrication through 3D printing breaks the illusion: 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 formulate balance optimization as an energy minimization, improving stability by modifying the *volume* of the object, while preserving its surface details. This takes place during interactive editing: the user cooperates with our optimizer towards the end result. We demonstrate 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., Sorkine-Hornung, O. 2013. Make It Stand: Balancing Shapes for 3D Fabrication. ACM Trans. Graph. 32, 4, Article 81 (July 2013), 10 pages. DOI = 10.1145/2461912.2461957 http://doi.acm.org/10.1145/2461912.2461957

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DOI: http://doi.acm.org/10.1145/2461912.2461957

1 Introduction

Balance is a delicate compromise between shape, weight and pose. It is therefore difficult to visually assess whether a given object is properly balanced and will stand in a stable, up-right position. Artists, designers and architects use this to their advantage to produce surprising and elegant designs that seem to defy gravity [Smithson 1968; von Meiss 1990; Kedziora 2011]. A well-known design principle to this effect, *asymmetric balance* [Lauer and Pentak 2011], consists in achieving balance by contrasting sizes and weights on either side of a composition. When considering physical objects, this process is not only concerned with aesthetics, but also with structural soundness: the weights of each part must exactly compensate each other, balancing the design in its intended, stable pose.

With the advent of 3D printing technologies, it becomes very simple to produce physical realizations of 3D models. Unfortunately, they most often fail to stand, making it mandatory to glue the printed objects onto a heavy pedestal. The delicate process of balancing, already difficult with physical objects, is very challenging when manipulating geometry in a 3D modeler. There is usually no indication of gravity, support or weight. Volumes are only represented by their boundaries, making it tedious to exploit degrees of freedom such as carving the inside of an object to change its weight distribution.

In this paper, we propose to assist users in modifying existing 3D models to create novel, balanced designs. Using our approach, the user interactively edits a shape and cooperates with our optimizer towards the final result. The optimizer constantly improves the design to ensure that, after printing, it will stand on its intended basis with the chosen orientation. This is especially well suited for the modeling of surprising asymmetric balance configurations, such as the printed horse model in Figure 1.

The input to our algorithm is a surface mesh representing a solid object, a number of desired contact points and the desired orientation (i.e., gravity direction). We exploit two main degrees of freedom when modifying the model: our algorithm *carves* and *deforms* the object to improve its equilibrium. We seek to minimize deviations from the intended shape, and therefore the algorithm searches for a compromise between removing matter from the interior and de-

ACM Transactions on Graphics, Vol. 32, No. 4, Article 81, 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.*

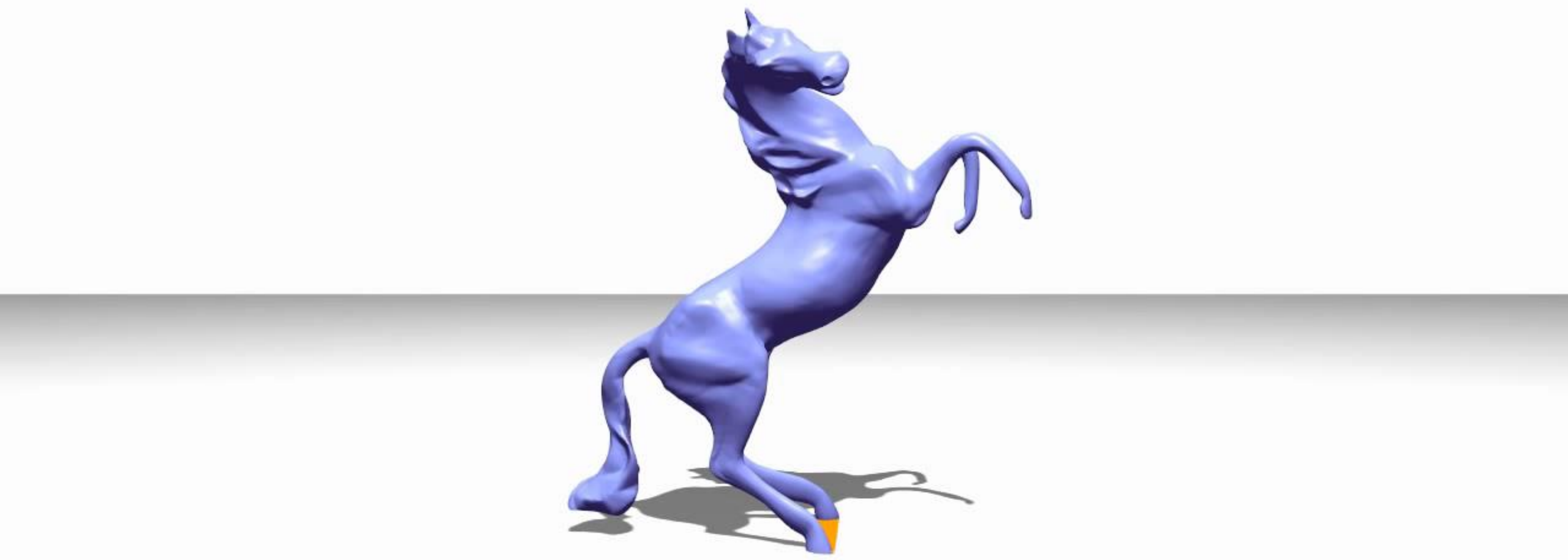
Figure 8: *Armadillo model with different starting poses. (Left) Unstable input. (Middle) Balanced result. (Right) Printed model.*

Contributes a new algorithm for balance optimization using infill operations

Validates approach via demonstration on a variety of models.

Source: Prévost *et al.*, Make it stand: balancing shapes for 3D fabrication. ACM Trans Graphs 2013

MODIFYING INFILL & SHAPE TO IMPROVE OBJECT BALANCE



Source: Prévost *et al.*, ACM Trans. Graph.'13; https://youtu.be/_drZksLRx94

SUPPORTING ITERATION

PATCHING 3D-PRINTED OBJECTS

Patching Physical Objects

Alexander Teibrich[1], Stefanie Mueller[1], François Guimbretière[1,2], Robert Kovacs[1], Stefan Neubert[1], Patrick Baudisch[1]

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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 parts 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 accomplishes this: Users mount the existing object into 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 the system's built-in 3D scanner. After calibrating 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 inexperienced users will create their own designs using software that enables them to create objects through a design-fabricate-test-redesign cycle [4].

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DOI: http://dx.doi.org/10.1145/2807442.2807467

Figure 1: To minimize material consumption and to reduce waste during design iteration, 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.

While we share the excitement about this future evolution, we are worried about potential implications on sustainability: unlike the more "traditional" software-based design process, creating and iterating on physical designs requires actual physical material and creates actual physical waste.

Existing angles on sustainability focus on either reducing print material (e.g. infill material [27], support material [24]) or they try to recycle the already printed material. While a few filament types, such as PLA, are biodegradable, many other materials are not. Filament extruders, such

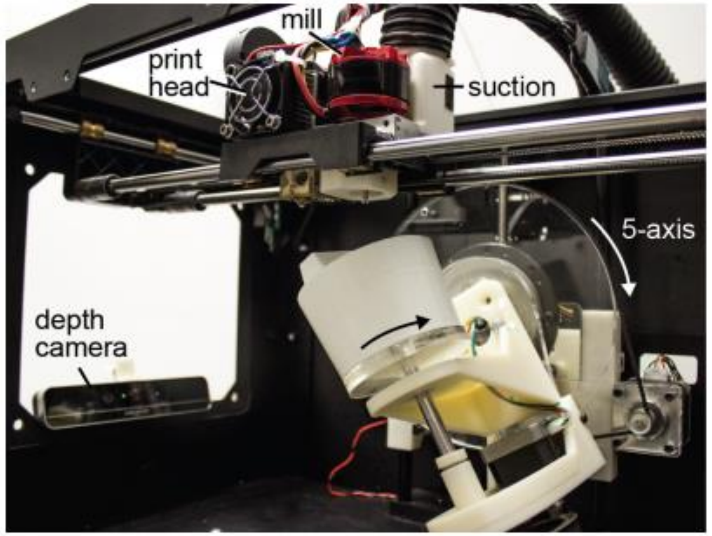


Figure 2: Hardware for patching physical objects.

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

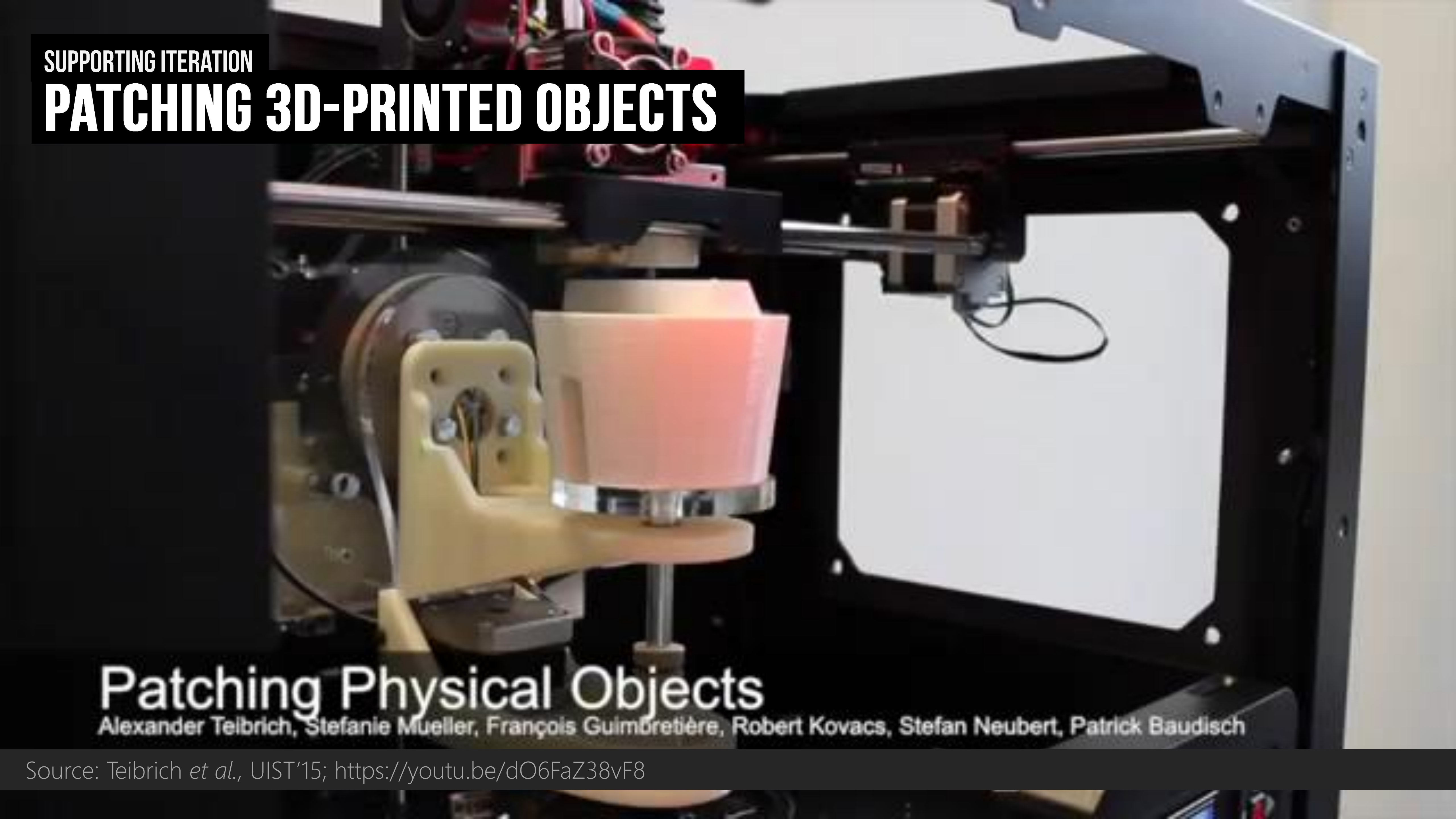
Custom fabrication machine can scan and mill previously printed parts to improve/repair

Reduces material consumption and waste

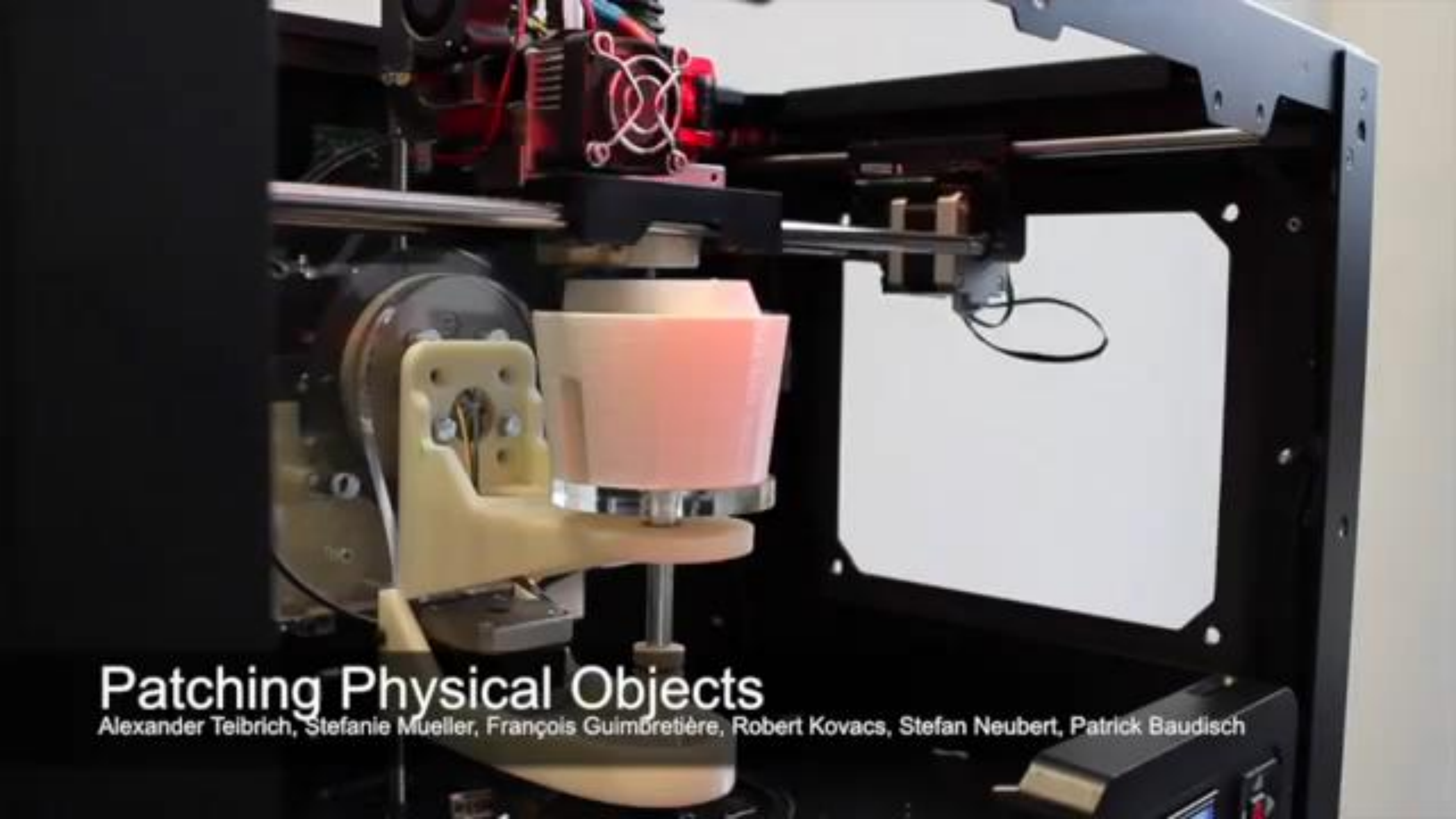
Source: Teibrich *et al.*, Patching Physical Objects, UIST'15

SUPPORTING ITERATION

PATCHING 3D-PRINTED OBJECTS



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


Patching Physical Objects
Alexander Teibrich, 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

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Carnegie Mellon University
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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 more 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 framework for 3D 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 supports a set of analysis metrics relating to *viability*, *durability* and *usability* that are visualized 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 original object. Our validation helps to illustrate the strengths and weaknesses 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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INTRODUCTION
As low-cost fabrication technology (*e.g.*, desktop 3D printers) becomes increasingly accessible, end-users have begun to adopt and use it to create physical objects of their own design. In the future, we can expect a wide range of objects to be designed and fabricated right on our desktop. However, existing use of 3D printing technology primarily focuses on *creating new objects from scratch*. This oversimplified assumption precludes the possibility that *existing objects* can also be extended, repaired or more generally modified to fulfill additional purposes. Being able to augment these existing objects rather than remaking them presents a more sustainable option for fabrication and, further, avoids unnecessarily replacing objects that might be of personal value to the users.

Fabricating parts to augment existing objects would require amongst other things an understanding of what *attachment* techniques can be used to join one object to another. There are a myriad of ways to fasten or attach two objects together from anchor bolts to zippers (see for example: [1, 5]), and adopting any of them to fit and attach to an existing object requires careful consideration of a range of issues such as viability, durability, and usability/semantics.

In this paper, we present three specific attachment techniques enabled by a unified computational framework: i) *print-over* prints attachments directly onto the surface of an object, such as printing a magnet holder to a Teddy bear (Figure 1b); ii) *print-to-affix* fabricates parts which are separately attached using straps or adhesive, such as adding a structure to make a glue gun stand (Figure 1c); iii) *print-through* prints an attachment through and around a hole of an existing object to interlock with it, such as printing a label into a the handle of a pair of scissors (Figure 1d).

These attachment techniques were integrated into Encore, a tool that can import a 3D model of an existing object, perform geometric analyses for the attachment techniques, and allow user exploration through visualization and direct

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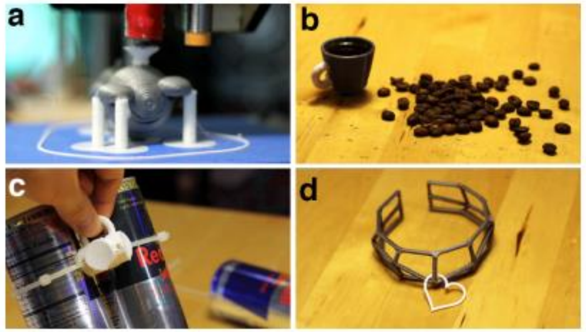


Figure 3. a) The magnet holder printed directly on a teddy bear that was scaffolded on support structures; b) a handle added to an espresso cup; c) strapping to make a reusable "4 pack" handle; and d) a bracelet printed through a heart-shaped charm.

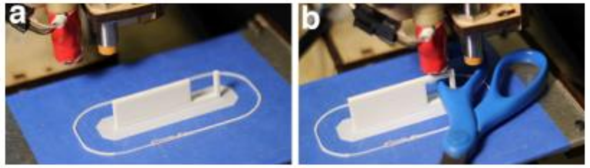


Figure 4. Example of a print-through process: the printer pauses at a point where the scissors can be dropped to interlock with the name tag, after which the print job resumes.

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

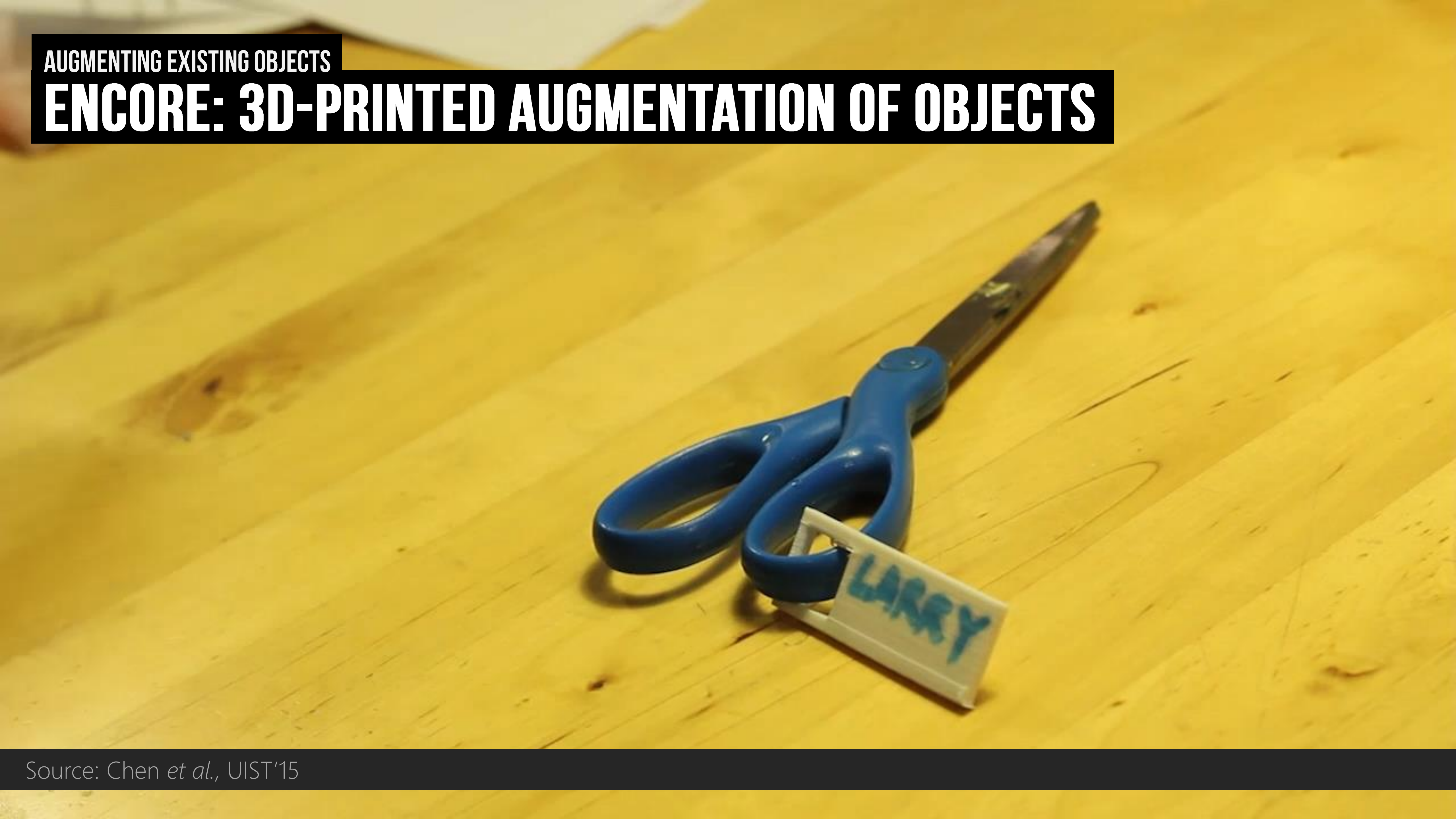
Distills three key attachment techniques: *print-over*, *print-to-affix*, and *print-through*

Provides a custom design tool

Source: Chen *et al.*, Encore: 3D Printed Augmentation of Everyday Objects with Printed-Over, Affixed and Interlocked Attachments, UIST'15

AUGMENTING EXISTING OBJECTS

ENCORE: 3D-PRINTED AUGMENTATION OF OBJECTS



Source: Chen *et al.*, UIST'15


LARRY

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

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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

be out of reach for a child, thus it needs to be extended[1] (Figure 2a); it is hard to hold a drill bit straight while sharpening it, thus a guide comes in handy to keep it in place[2] (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-gun[3] (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

Source: Tom Yeh, University of Colorado, https://tactilepicturebooks.org/

Facade: Auto-generating Tactile Interfaces to Appliances

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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

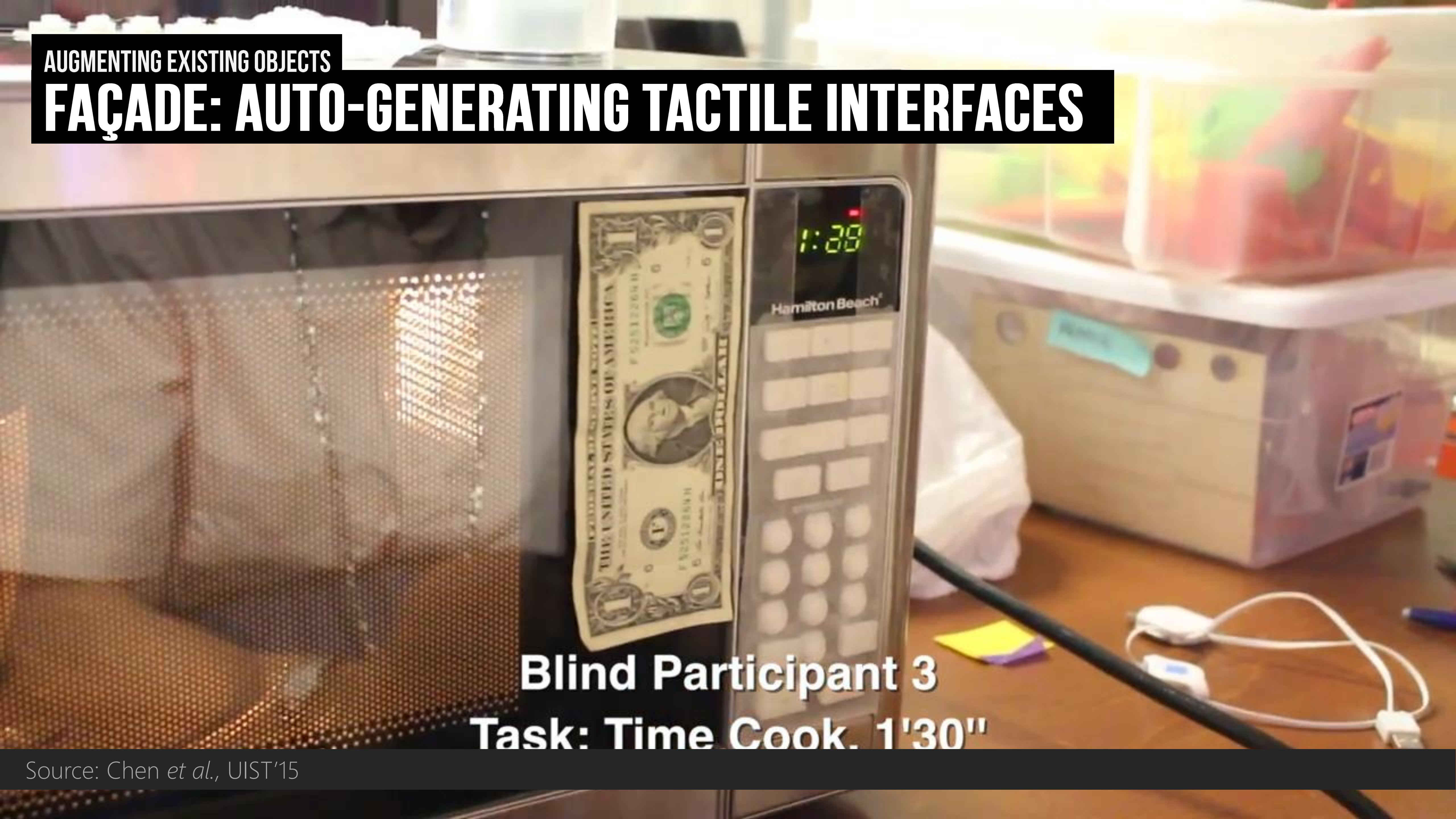
Common appliances have shifted toward flat interface panels, making them inaccessible to blind people. Although blind people can label appliances with Braille stickers, doing

Author Keywords

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

AUGMENTING EXISTING OBJECTS

FAÇADE: AUTO-GENERATING TACTILE INTERFACES



Source: Chen *et al.*, UIST’15


1:29
Hamilton Beach
Blind Participant 3
Task: Time Cook, 1'30''