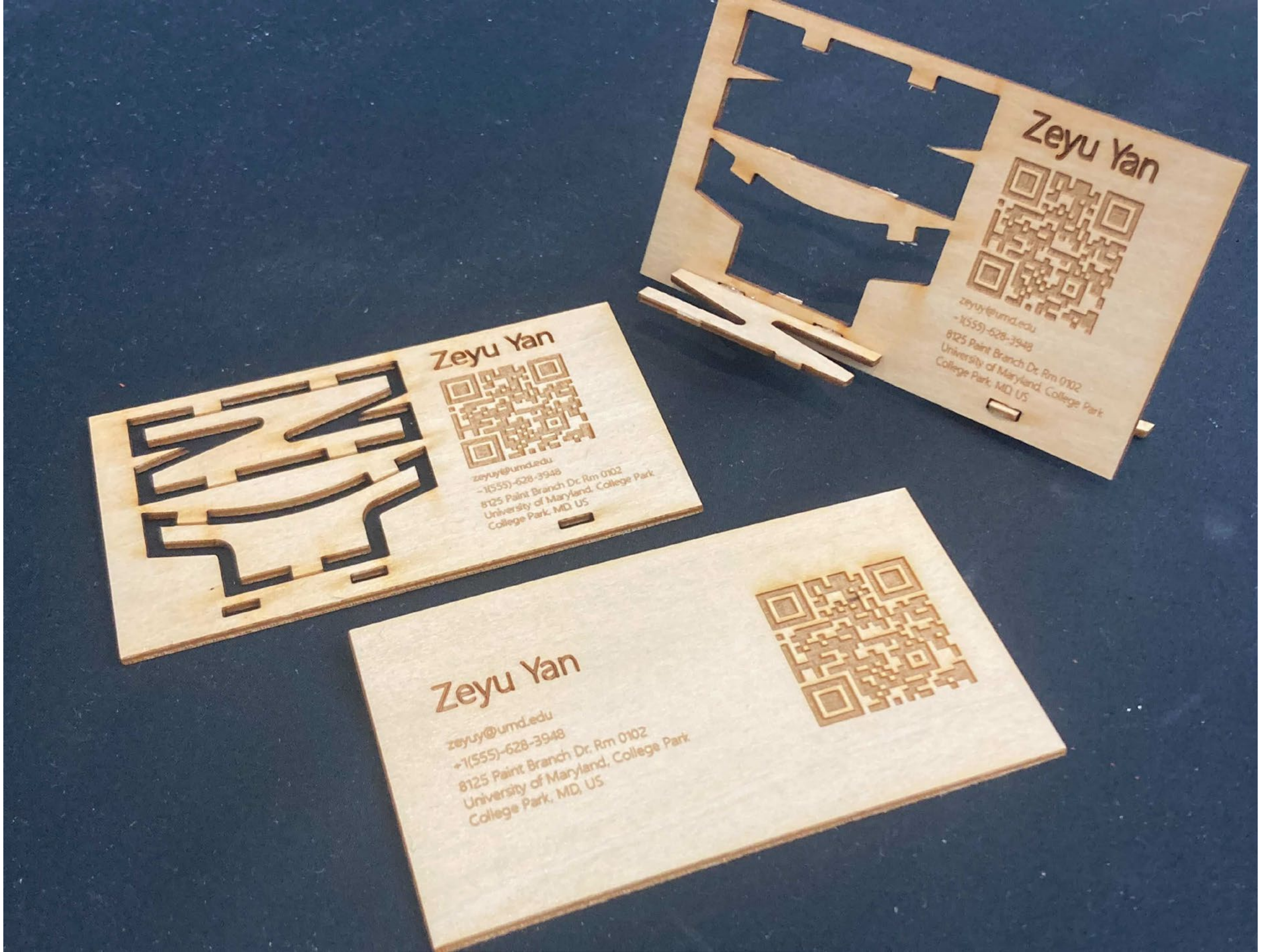
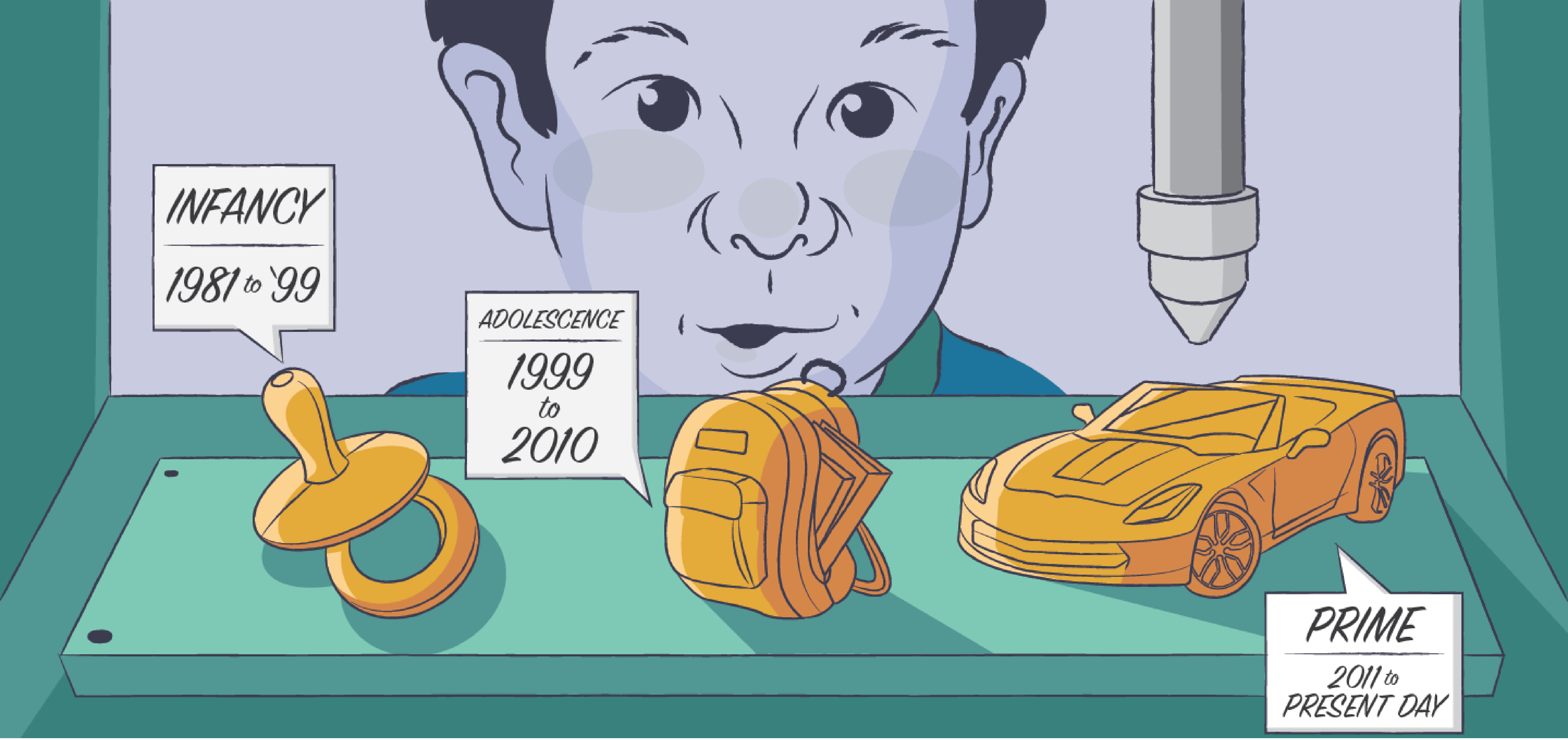
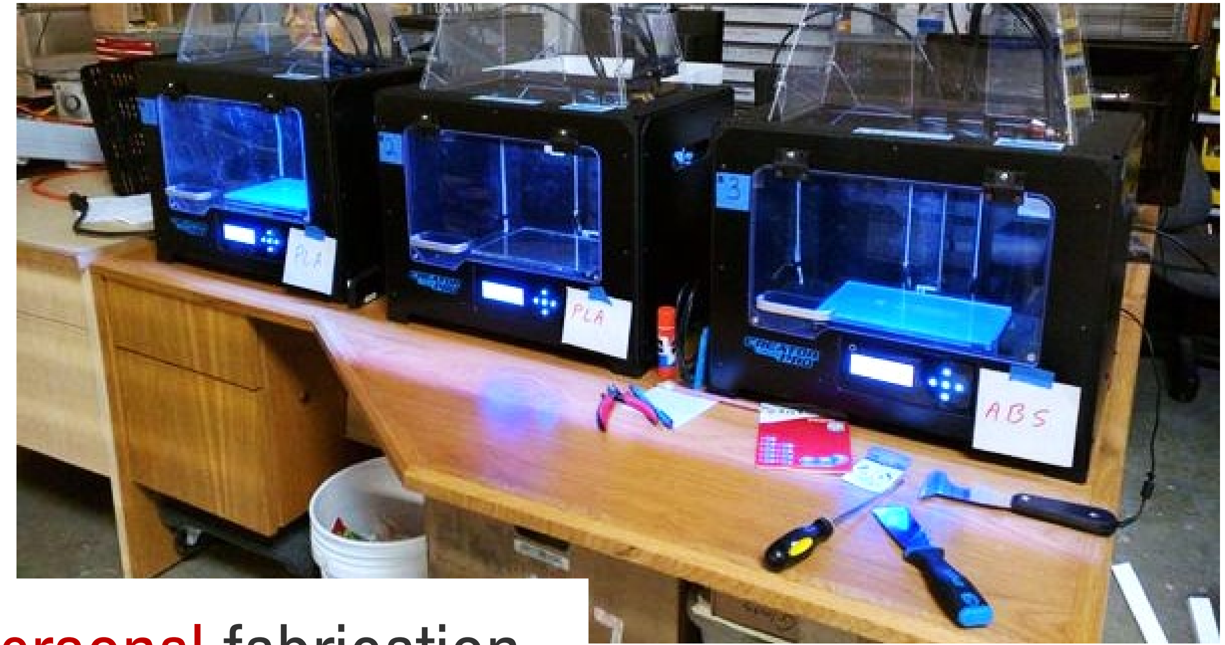

Zeyu Yan
zeyuy@umd.edu
+1(555)-628-3948
8125 Paint Branch Dr. Rm 0102
University of Maryland, College Park
College Park, MD, US



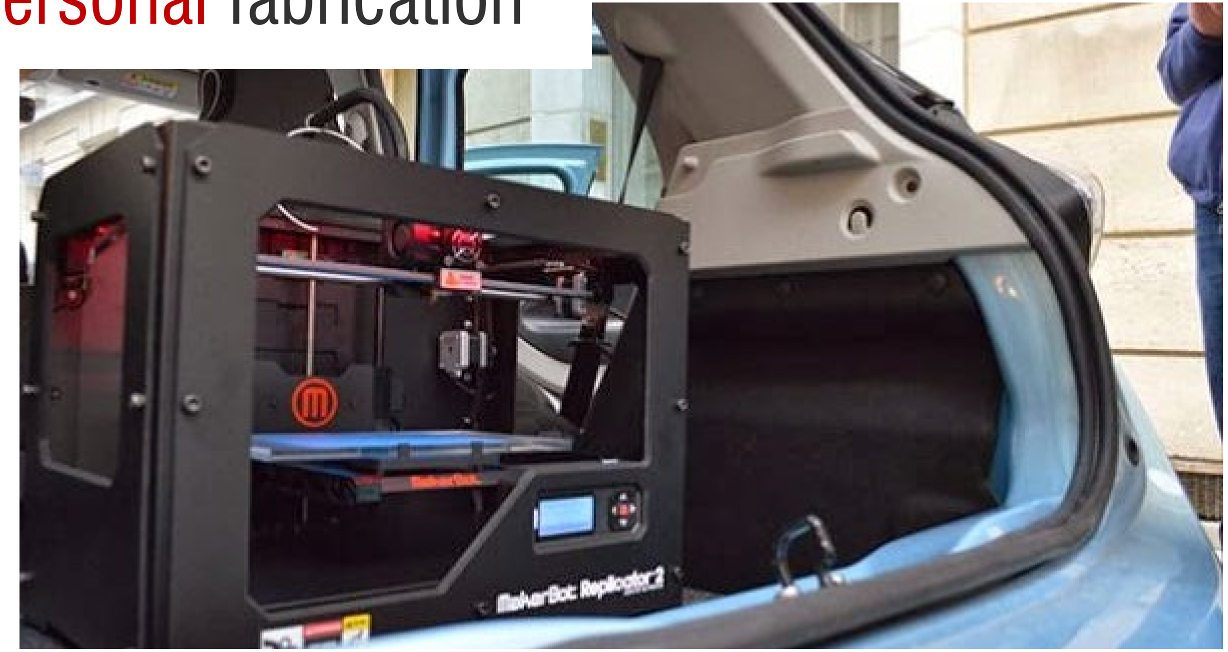
Fabrication + Interactivity

CMSC730 | Huaishu Peng | UMD CS

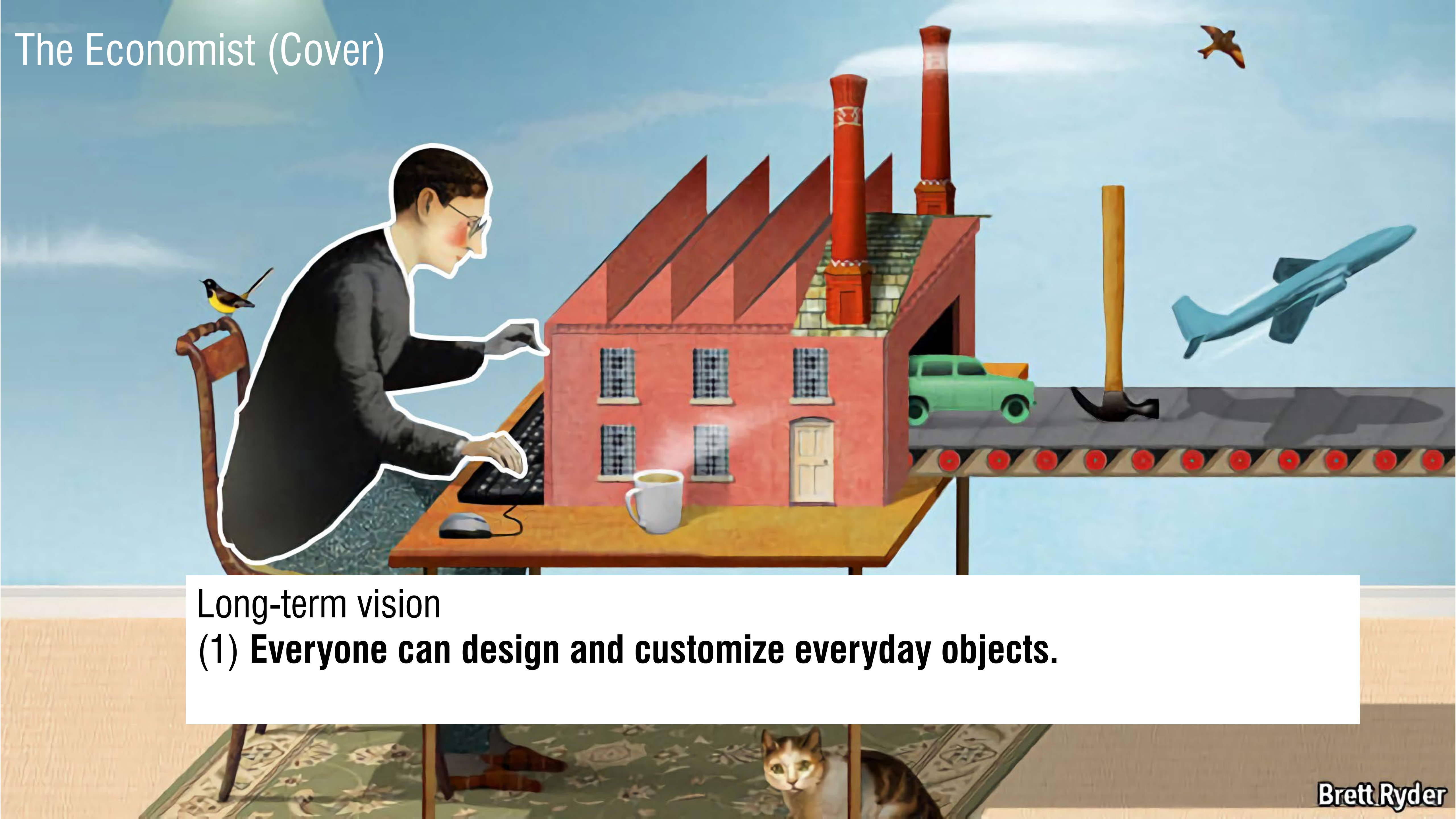
Industrial 3D Printer



The new era of personal fabrication



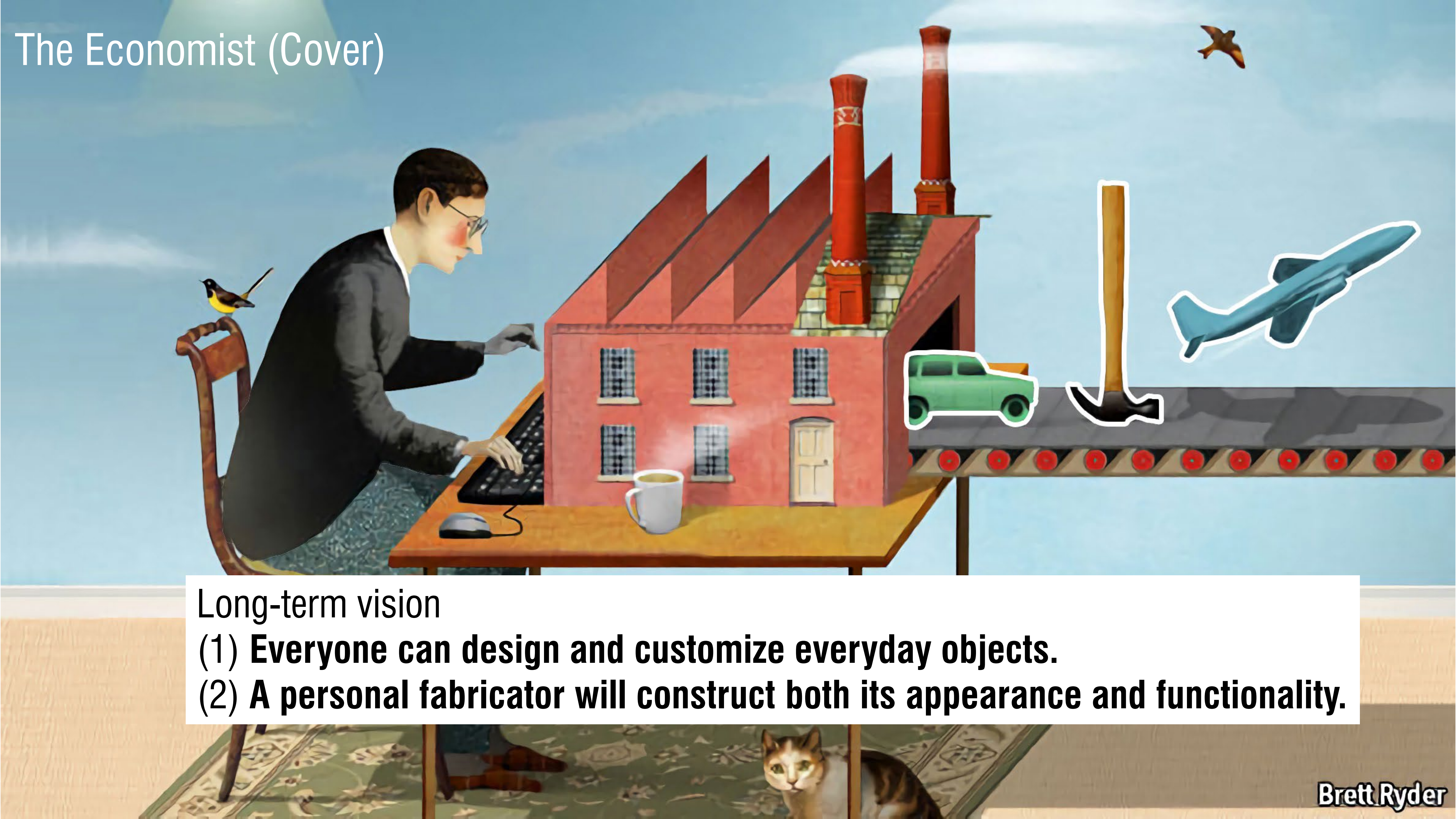
The Economist (Cover)



Long-term vision

(1) **Everyone can design and customize everyday objects.**

The Economist (Cover)



Long-term vision

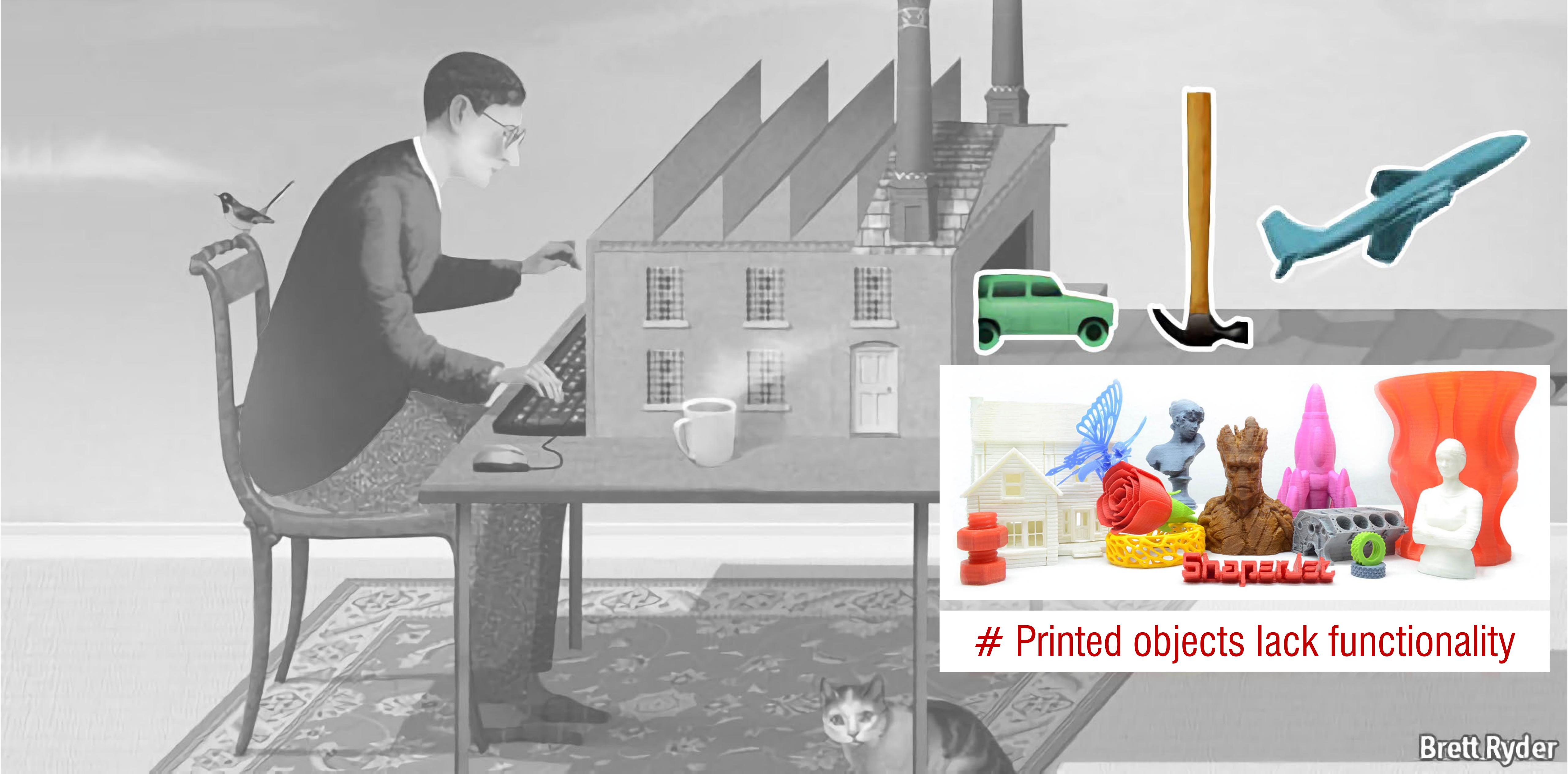
(1) **Everyone can design and customize everyday objects.**

(2) **A personal fabricator will construct both its appearance and functionality.**

Two challenges for personal fabrication

Design 3D digital models is difficult

Two challenges for Personal Fabrication



Printed objects lack functionality

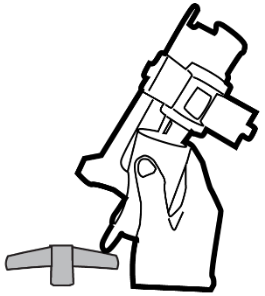
Fabrication

Fabrication + Interactivity

Fabrication + Interactivity

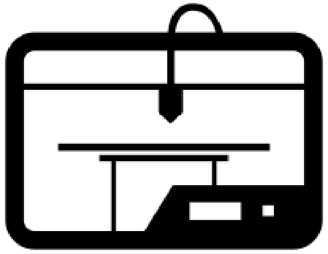
Interactive Fabrication

Lower the design barriers
for 3D modeling



Fabrication for Interaction

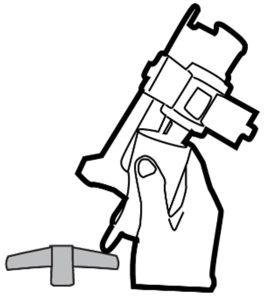
Raise the output capabilities
of a fabricated object



Fabrication + Interactivity

Interactive Fabrication

Lower the design barriers
for 3D modeling

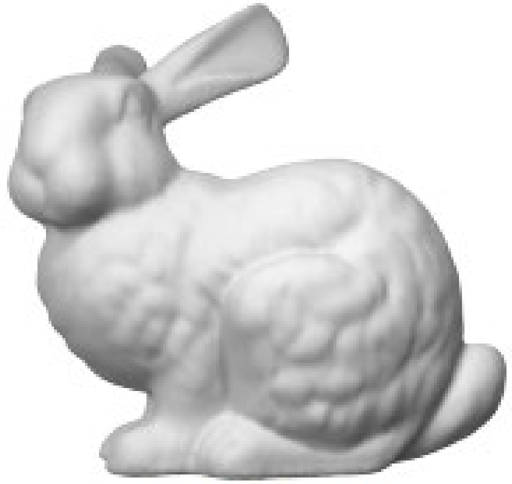


Fabrication for Interaction

Raise the output capabilities
of a fabricated object

What are the drawbacks of CAD design tools?

- Implicit design commands
- Complex interface
- No fast physical feedback (intimacy between the designer and the raw material)



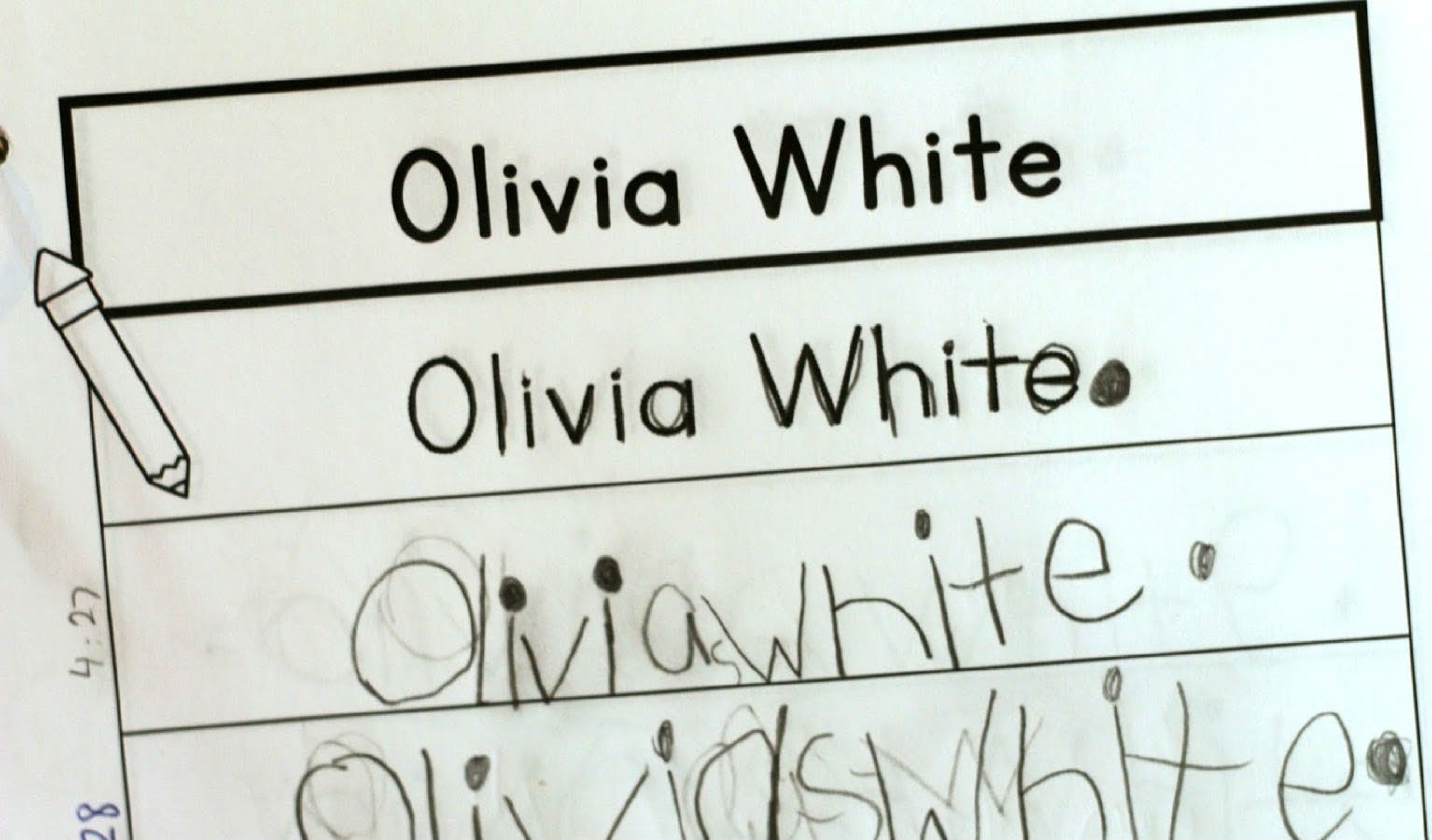
(a) Target 3D model

Input: 3D digital model

?

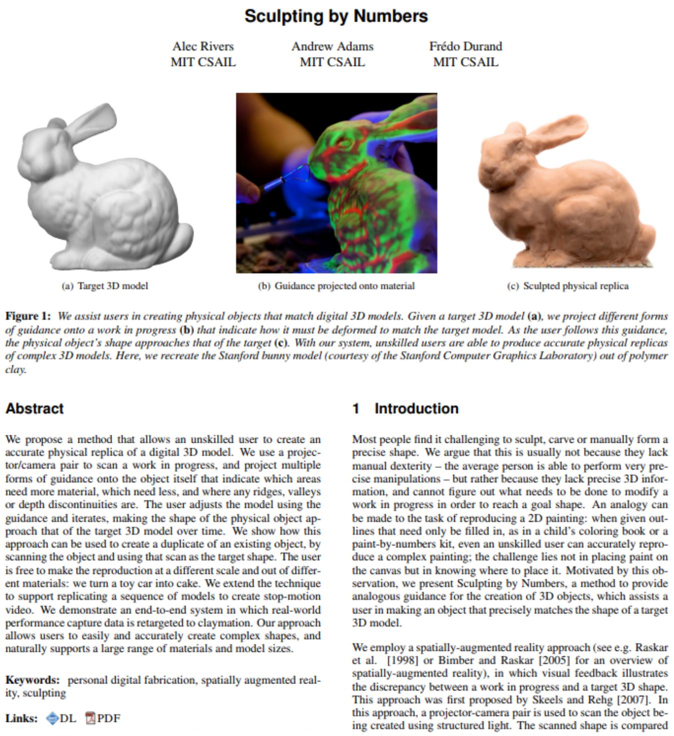
(c) Sculpted physical replica

Output: 3D clay model


Olivia White
Olivia White
4:27
28

(a) Target 3D model

(b) Guidance projected onto material



Sculpting by Numbers

Alec Rivers
MIT CSAIL

Andrew Adams
MIT CSAIL

Frédo Durand
MIT CSAIL

(a) Target 3D model

(b) Guidance projected onto material

(c) Sculpted physical replica

Figure 1: *We assist users in creating physical objects that match digital 3D models. Given a target 3D model* **(a)**, *we project different forms of guidance onto a work in progress* **(b)** *that indicate how it must be deformed to match the target model. As the user follows this guidance, the physical object's shape approaches that of the target* **(c)**. *With our system, unskilled users are able to produce accurate physical replicas of complex 3D models. Here, we recreate the Stanford bunny model (courtesy of the Stanford Computer Graphics Laboratory) out of polymer clay.*

Abstract

We propose a method that allows an unskilled user to create an accurate physical replica of a digital 3D model. We use a projector/camera pair to scan a work in progress, and project multiple forms of guidance onto the object itself that indicate which areas need more material, which need less, and where any ridges, valleys or depth discontinuities are. The user adjusts the model using the guidance and iterates, making the shape of the physical object approach that of the target 3D model over time. We show how this approach can be used to create a duplicate of an existing object, by scanning the object and using that scan as the target shape. The user is free to make the reproduction at a different scale and out of different materials: we turn a toy car into cake. We extend the technique to support replicating a sequence of models to create stop-motion video. We demonstrate an end-to-end system in which real-world performance capture data is retargeted to claymation. Our approach allows users to easily and accurately create complex shapes, and naturally supports a large range of materials and model sizes.

Keywords: personal digital fabrication, spatially augmented reality, sculpting

Links: DL PDF

1 Introduction

Most people find it challenging to sculpt, carve or manually form a precise shape. We argue that this is usually not because they lack manual dexterity – the average person is able to perform very precise manipulations – but rather because they lack precise 3D information, and cannot figure out what needs to be done to modify a work in progress in order to reach a goal shape. An analogy can be made to the task of reproducing a 2D painting: when given outlines that need only be filled in, as in a child's coloring book or a paint-by-numbers kit, even an unskilled user can accurately reproduce a complex painting; the challenge lies not in placing paint on the canvas but in knowing where to place it. Motivated by this observation, we present Sculpting by Numbers, a method to provide analogous guidance for the creation of 3D objects, which assists a user in making an object that precisely matches the shape of a target 3D model.

We employ a spatially-augmented reality approach (see e.g. Raskar et al. [1998] or Bimber and Raskar [2005] for an overview of spatially-augmented reality), in which visual feedback illustrates the discrepancy between a work in progress and a target 3D shape. This approach was first proposed by Skeels and Rehg [2007]. In this approach, a projector-camera pair is used to scan the object being created using structured light. The scanned shape is compared

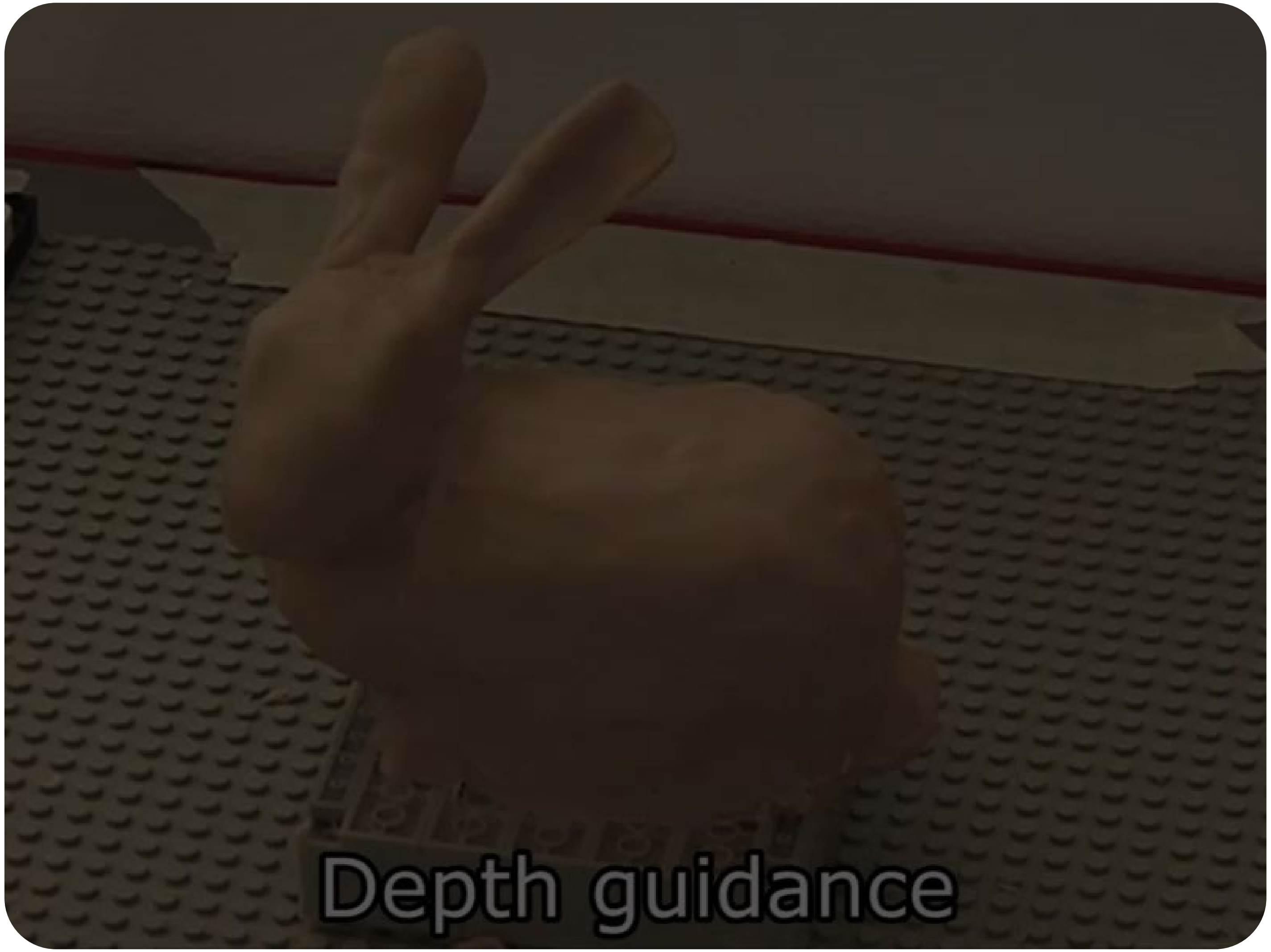
(c) Sculpted physical replica

Rivers et.al. from MIT
2012

Structured light 3D scanning

Compare the scanning result with the 3D digital model

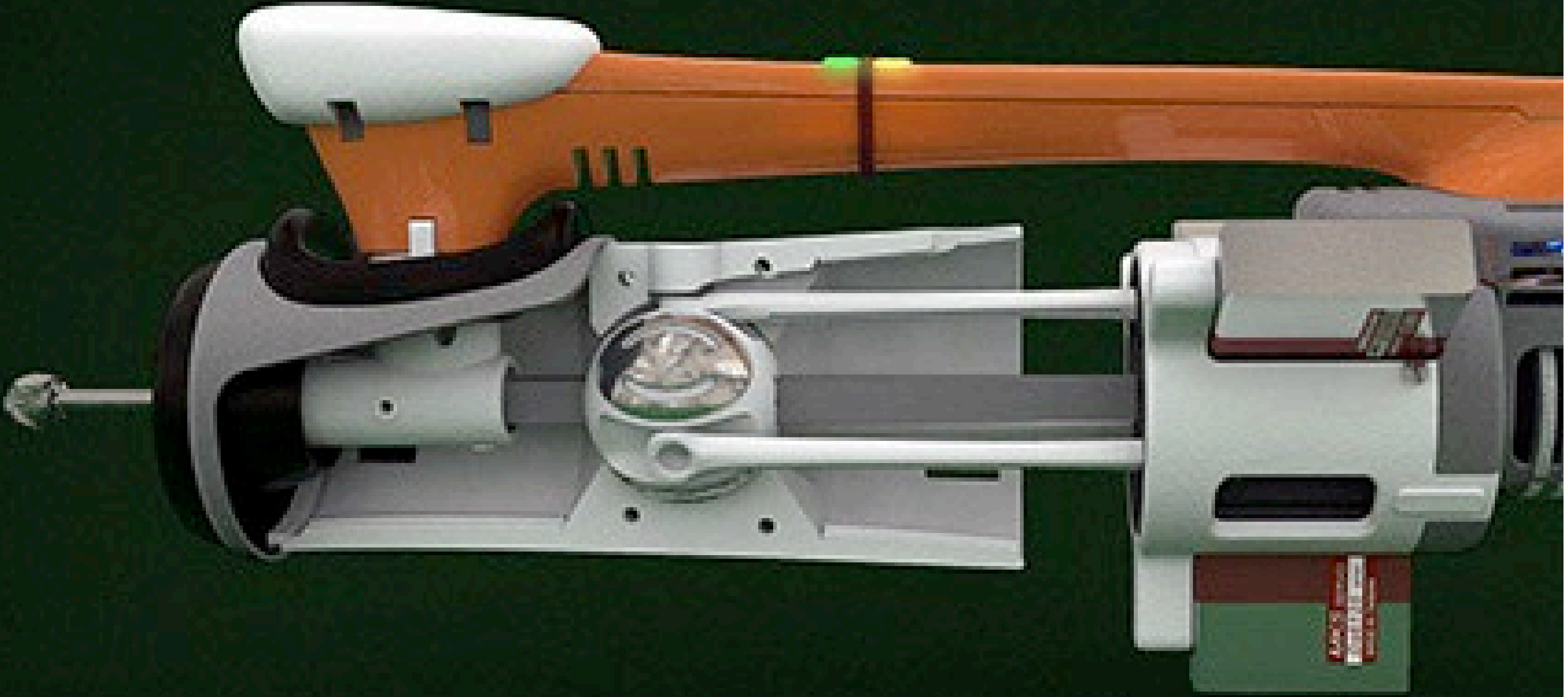
Differences are projected at each step with green/red colors



Limitations of this light guidance idea?

Turn-taking (scan at each of the ‘step’)
Would be hard to do with other material such as wood/foam (because there is no additive process for such material)

Possible solutions?



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.

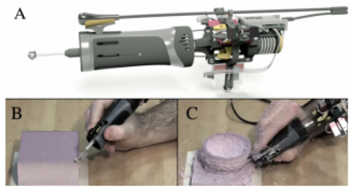
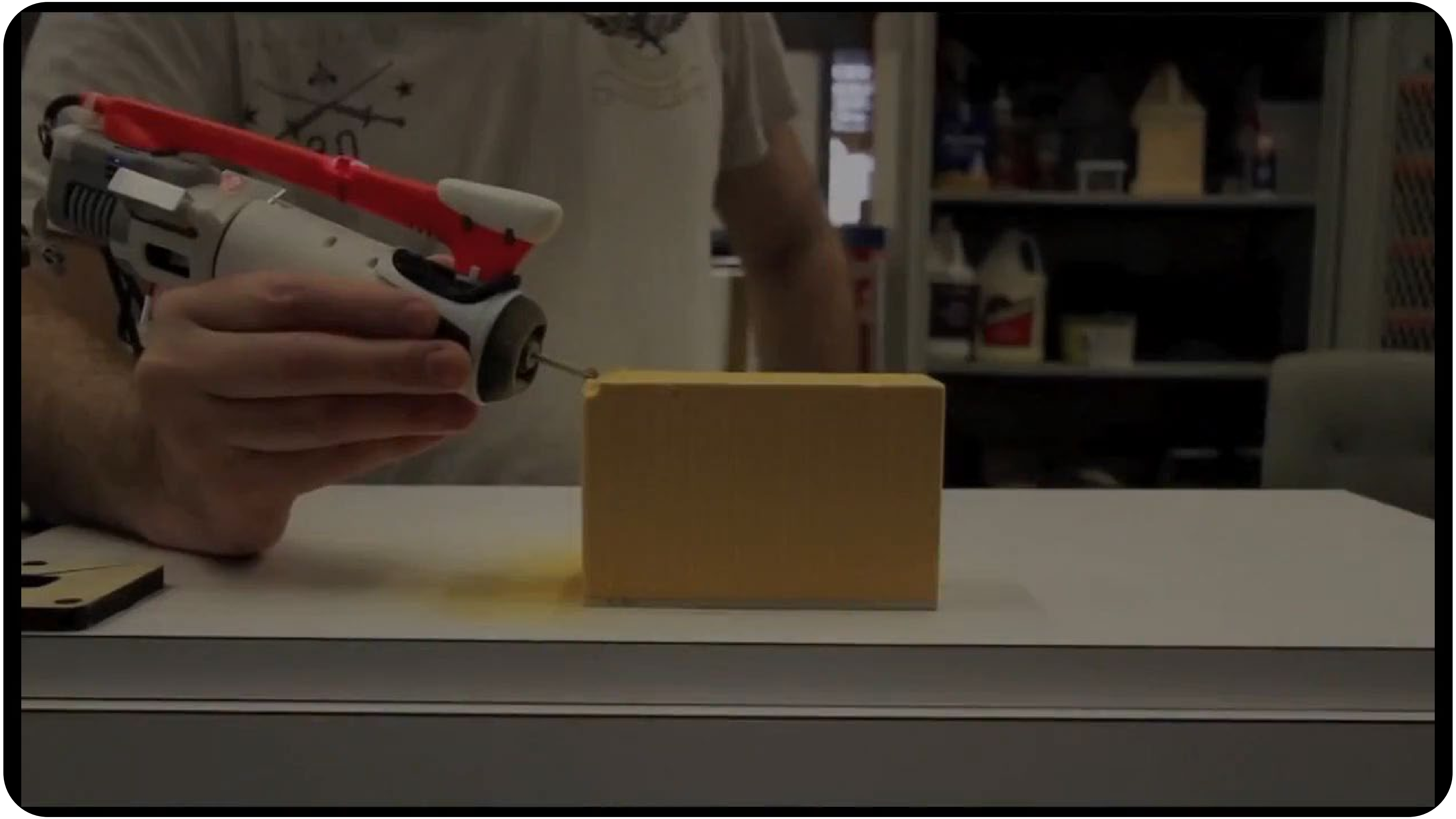
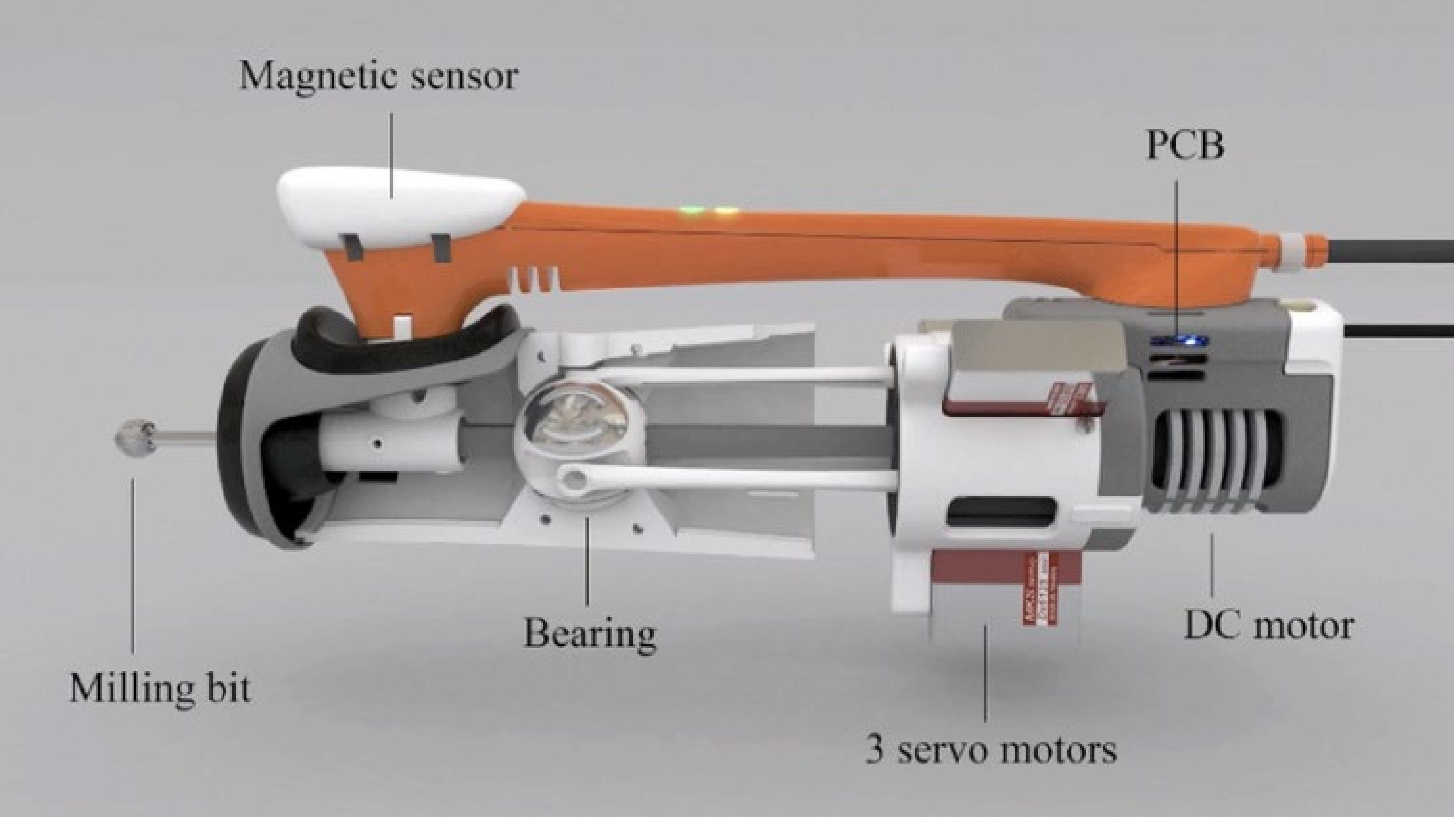


Figure 1: (A) The FreeD and (B-C) the process of making a bowl from polyethylene foam.

CHI 13 and UIST 13

Zoran et.al. from MIT

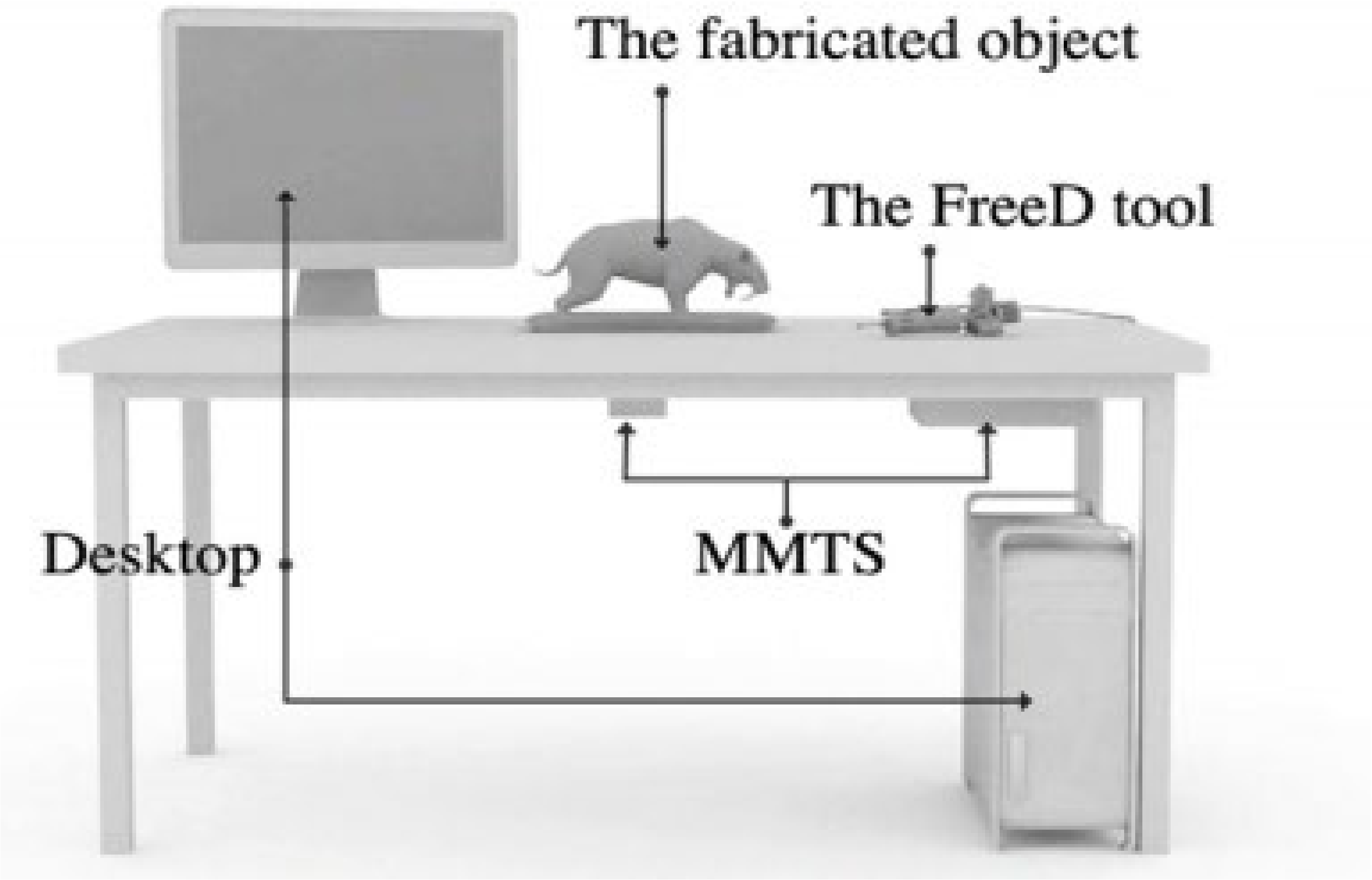



Magnetic sensor
PCB
Milling bit
Bearing
3 servo motors
DC motor

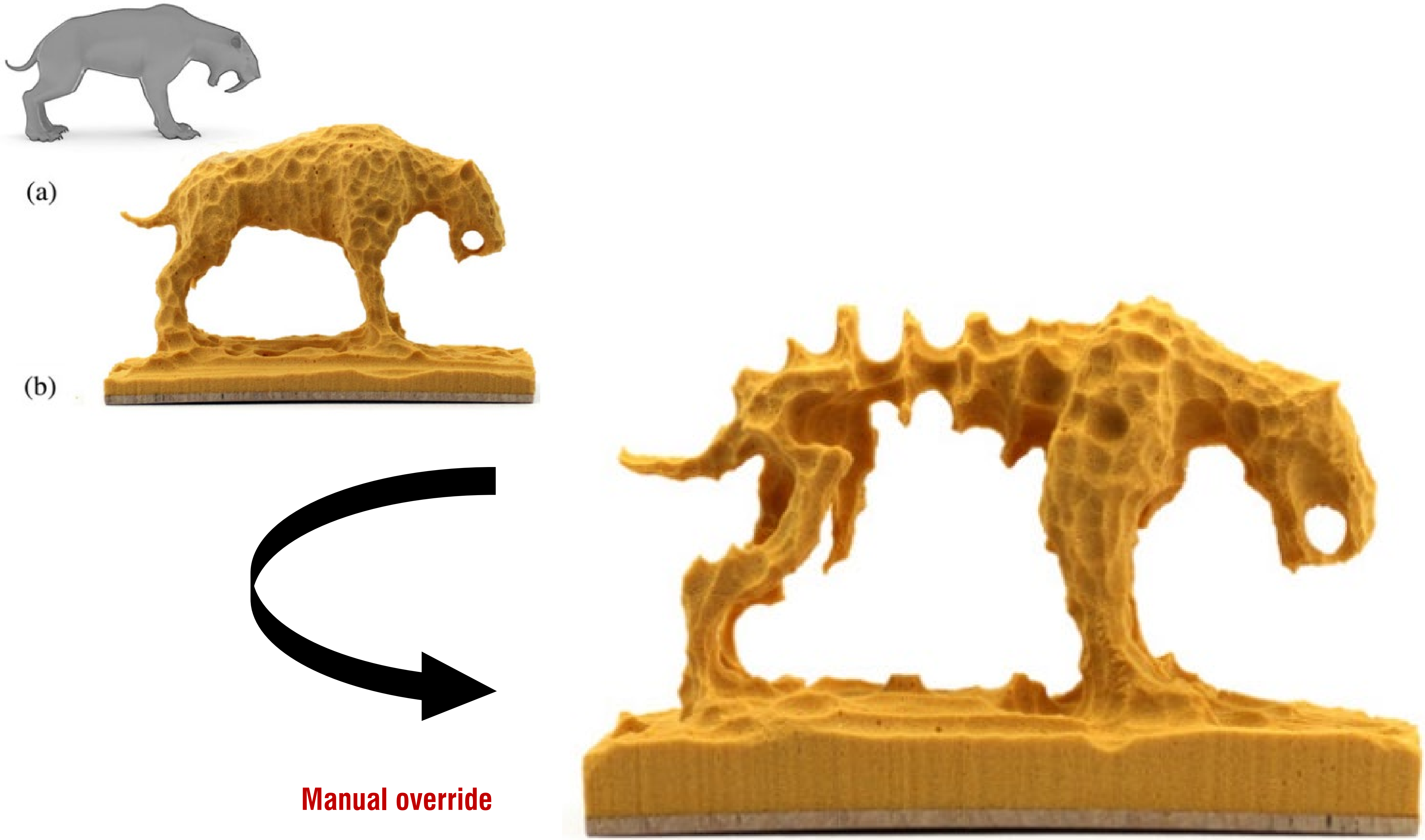
Tracking: 6DOF Magnetic tracking

Control: stop milling at the edge of the digital model

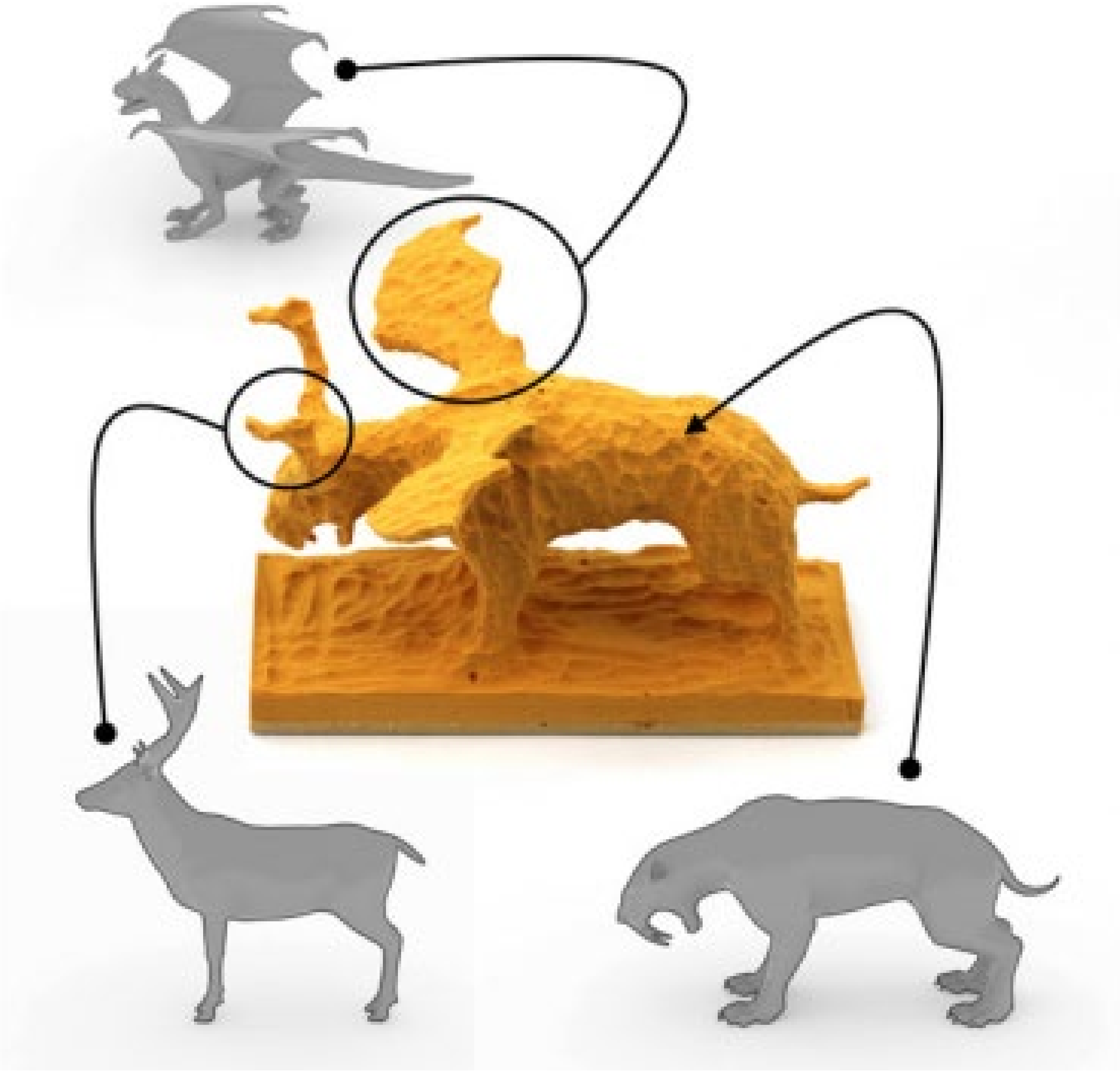
Control can be overridden with manual control



What can this do that the previous project cannot?


(a)
(b)
Manual override

user can manually switch between
different reference virtual models during the work



Physical merging

What if we have no digital model at the beginning?
What if we hope to design a 3D model **from scratch**?

D-Coil: A Hands-on Approach to Digital 3D Models Design

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François Guimbretière
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ABSTRACT

We introduce D-Coil, a new digital 3D modeling approach using wax coiling to bring tangibility to the design of digital models. After defining a shape to extrude, the users follow the lead of a hand-held actuated extruder to instantiate the actual extrusion using wax. The tangibility of the wax extrusion sets the stage to create the next components until the digital model is completed. The digital model affords all digital attributes (ease of transformation, distribution, and 3D printing) while the wax artifact can be discarded or kept as a one-of-a-kind memento. We present a proof-of-concept implementation of D-Coil and showcase how this additive approach can also be extended to a subtractive process using a digitally actuated cutter. By adding a 6DOF mouse, users can also include scaling, rotation, and bending effects to create a wide variety of shapes often difficult for novices to produce in standard CAD software.

Author Keywords

Computer-Aided Design (CAD); Craft; Digital Fabrication; Extrusion.

ACM Classification Keywords

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

INTRODUCTION

As predicted by Gershenfeld [5], we have seen a rapid advance towards the democratization of 3D printing in recent years. One can draw a parallel with the rise of desktop printing in the 1980's [1], with one significant difference: it is still difficult to create complex digital models ready for 3D printing. Though the interface of CAD systems has been greatly improved, the learning curve remains steep and creating complicated, smooth shapes requires the mastery of complex construction commands (such as lofting between multiple contours using guide rails). Further, the isolation of the design and fabrication process in digital CAD software makes it difficult for all

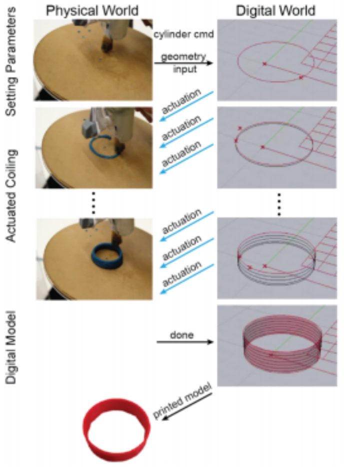
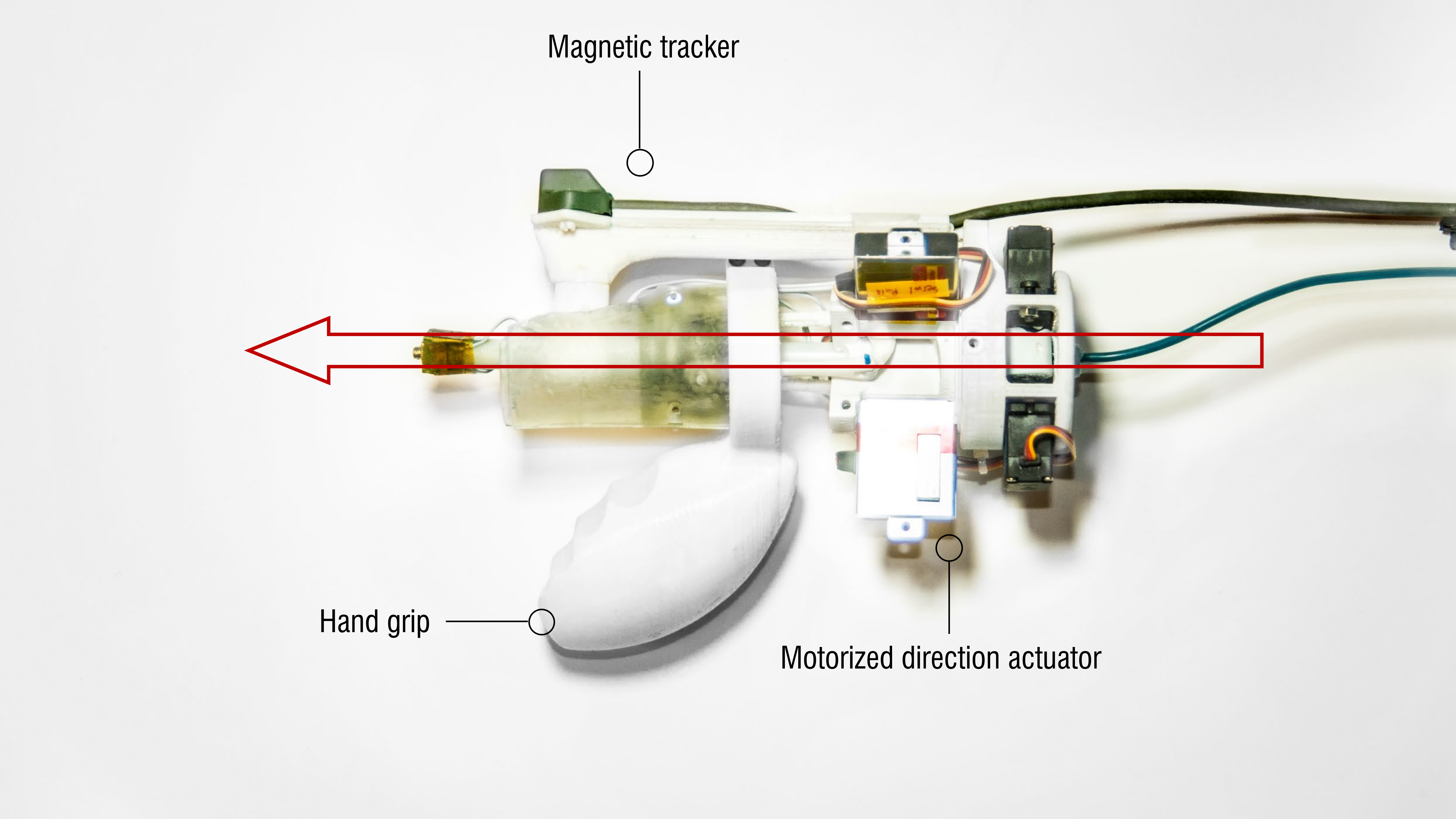


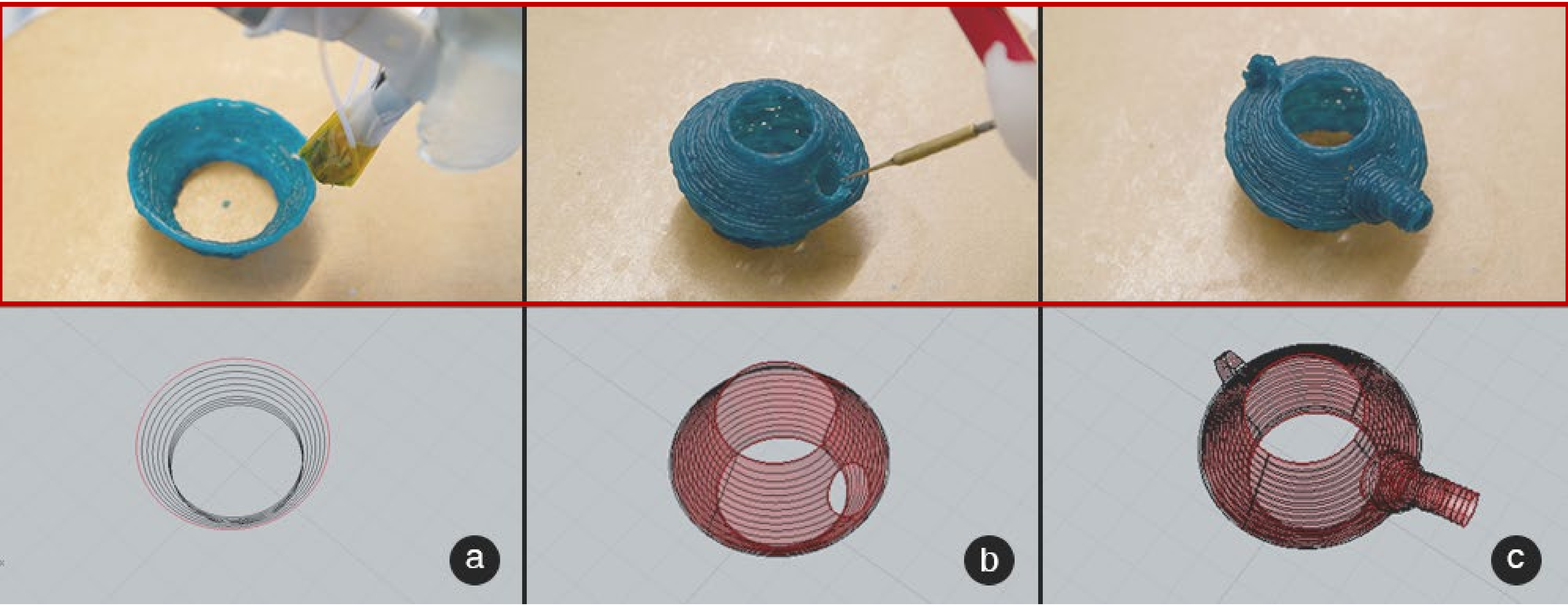
Figure 1: D-Coil concept: supporting 3D design using a wax proxy.

but experts to anticipate how a digital model will look and feel once it is built. This stands in sharp contrast with traditional craft activities such as clay coiling in which design and construction can occur at the same time. As observed by Schön [15], the intimate interaction between the designer and the material at hand establishes a constant reflective "conversation" promoting a faster convergence towards a satisfactory design. Clay coiling also has the advantage of being easy to learn for beginners (low floor), but offering sufficient flexibility to enable experts to create highly complex models (high ceiling) [13].

CHI 15
Peng et.al.

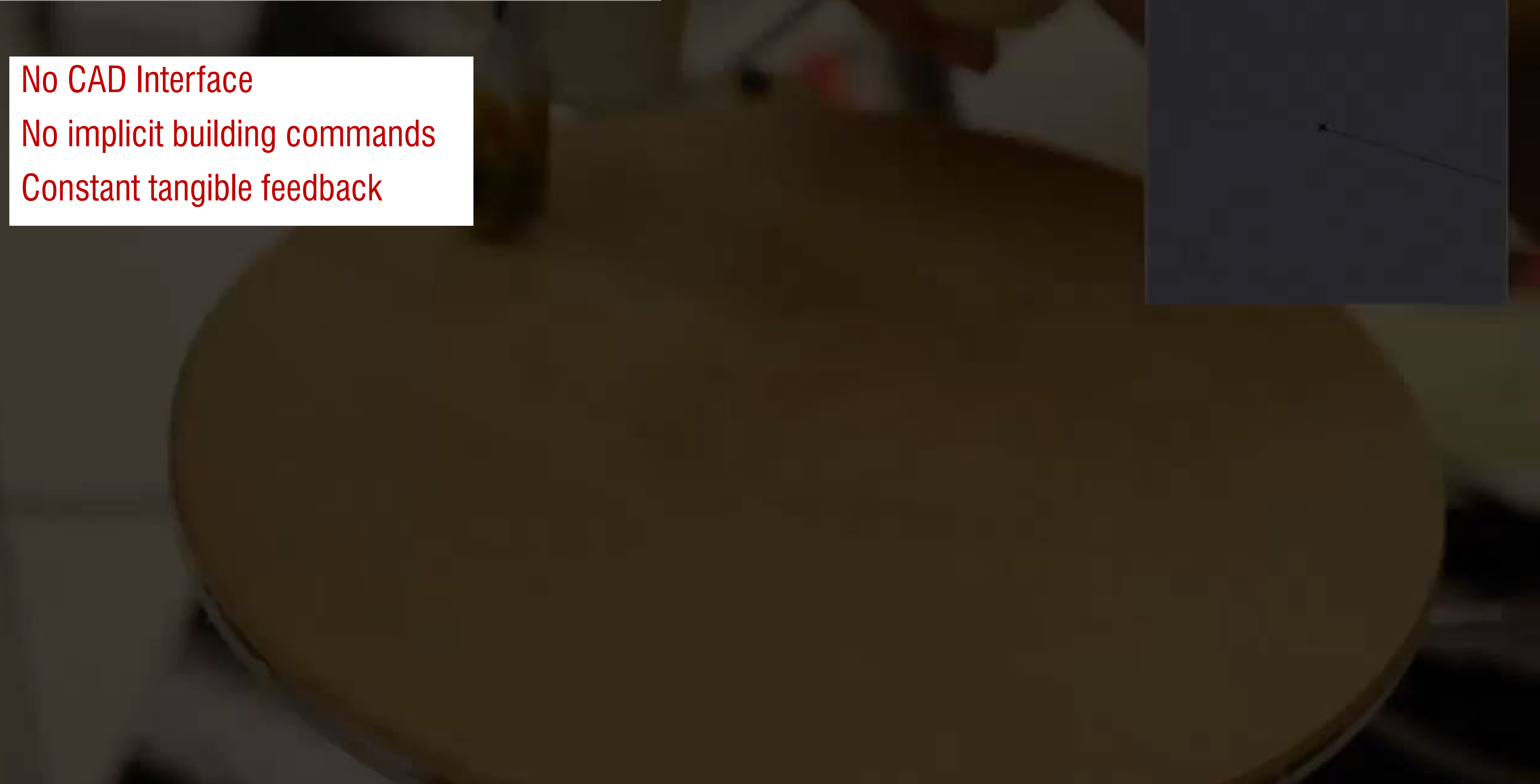


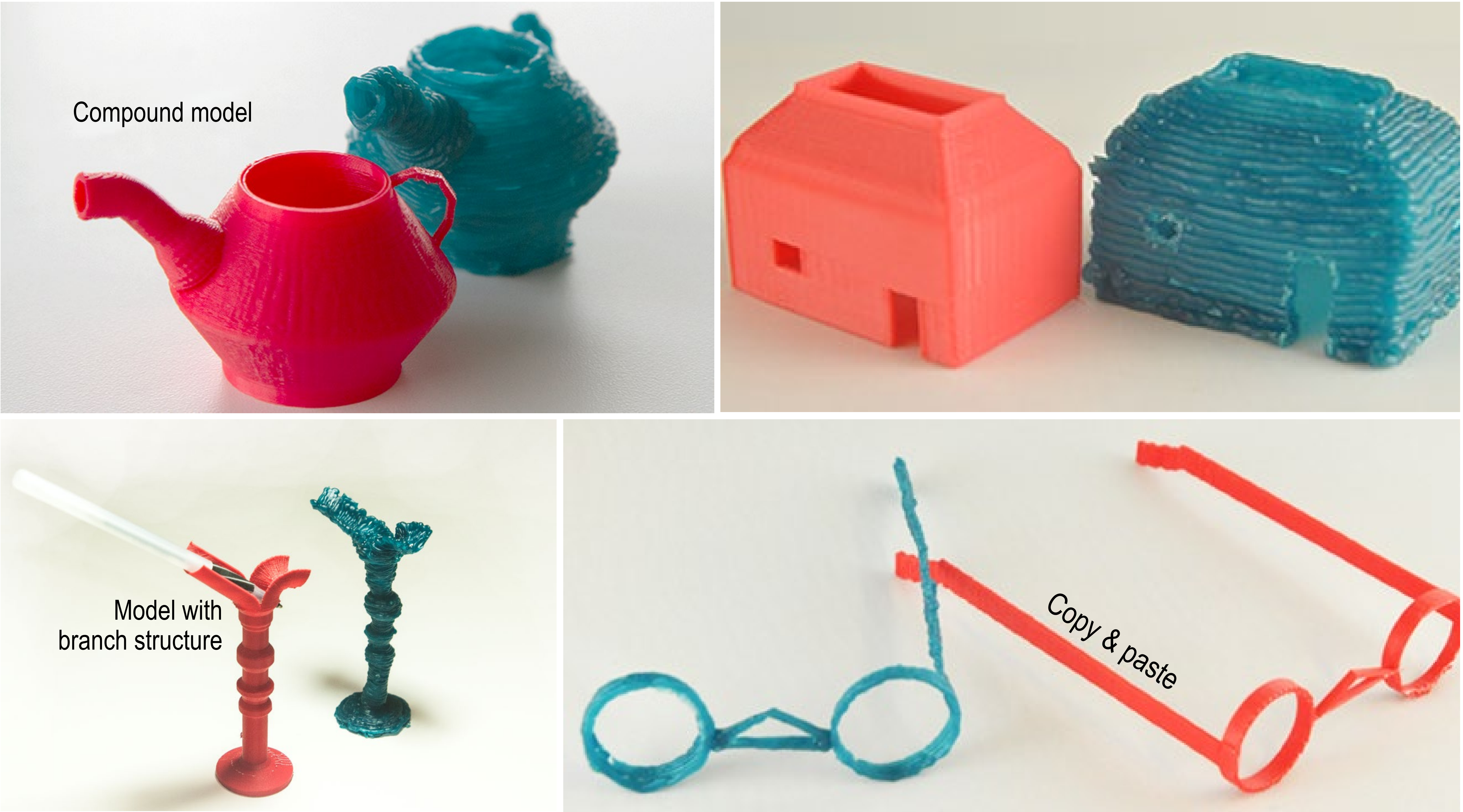
Magnetic tracker
Hand grip
Motorized direction actuator


a
b
c

3D modeling with no CAD interface

- No CAD Interface
- No implicit building commands
- Constant tangible feedback



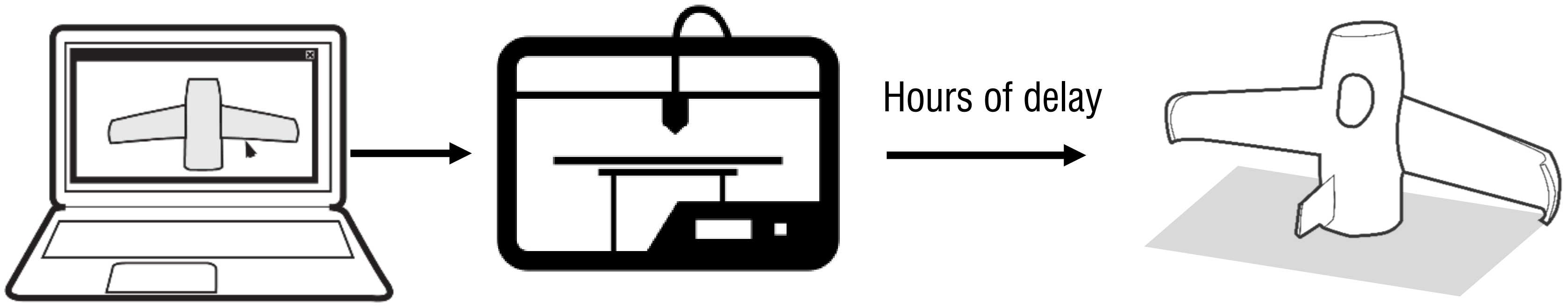

Compound model
Model with
branch structure
Copy & paste

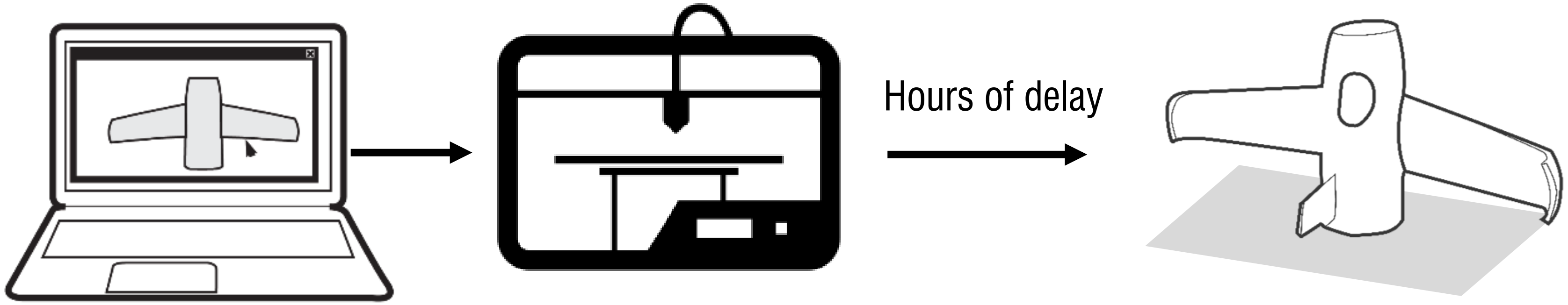
D-Coil

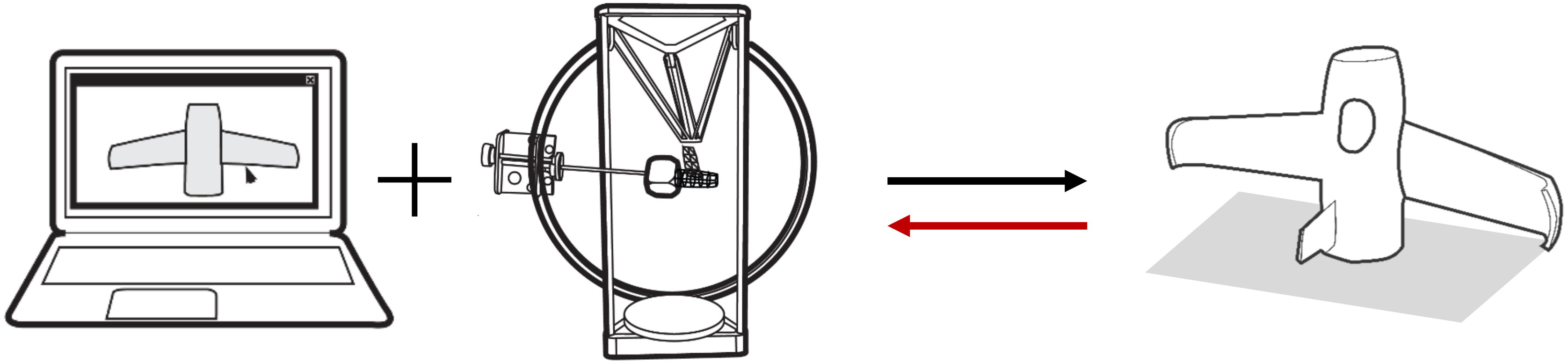
No CAD interface
Digitalization

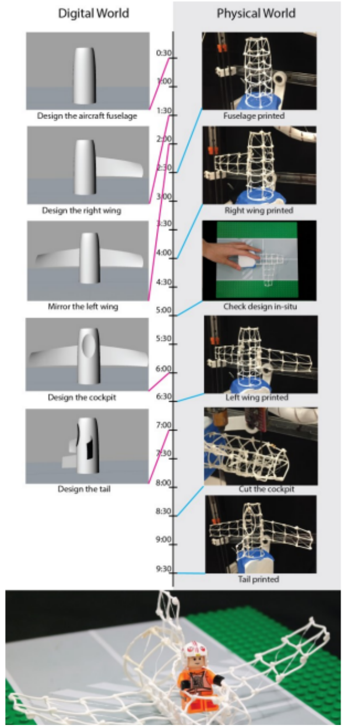
Slow in building speed
Not for CAD users

What if we can have a system **for CAD users** but with timely **physical feedback**?




Hours of delay





On-The-Fly Print: Incremental Printing While Modeling

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ABSTRACT

Current interactive fabrication tools offer tangible feedback by allowing users to work directly on the physical model, but they are slow because users need to participate in the physical instantiation of their designs. In contrast, CAD software offers powerful tools for 3D modeling but delays access to the physical workpiece until the end of the design process.

In this paper we propose *On-the-Fly Print*: a 3D modeling approach that allows the user to design 3D models digitally while having a low-fidelity physical wireframe model printed in parallel. Our software starts printing features as soon as they are created and updates the physical model as needed. Users can quickly check the design in a real usage context by removing the partial physical print from the printer and replacing it afterwards to continue printing. Digital content modification can be updated with quick physical correction using a retractable cutting blade. We present the detailed description of *On-the-Fly Print* and showcase several examples designed and printed with our system.

Author Keywords
3D printing; fabrication; computational craft; CAD; rapid prototyping; interactive devices.

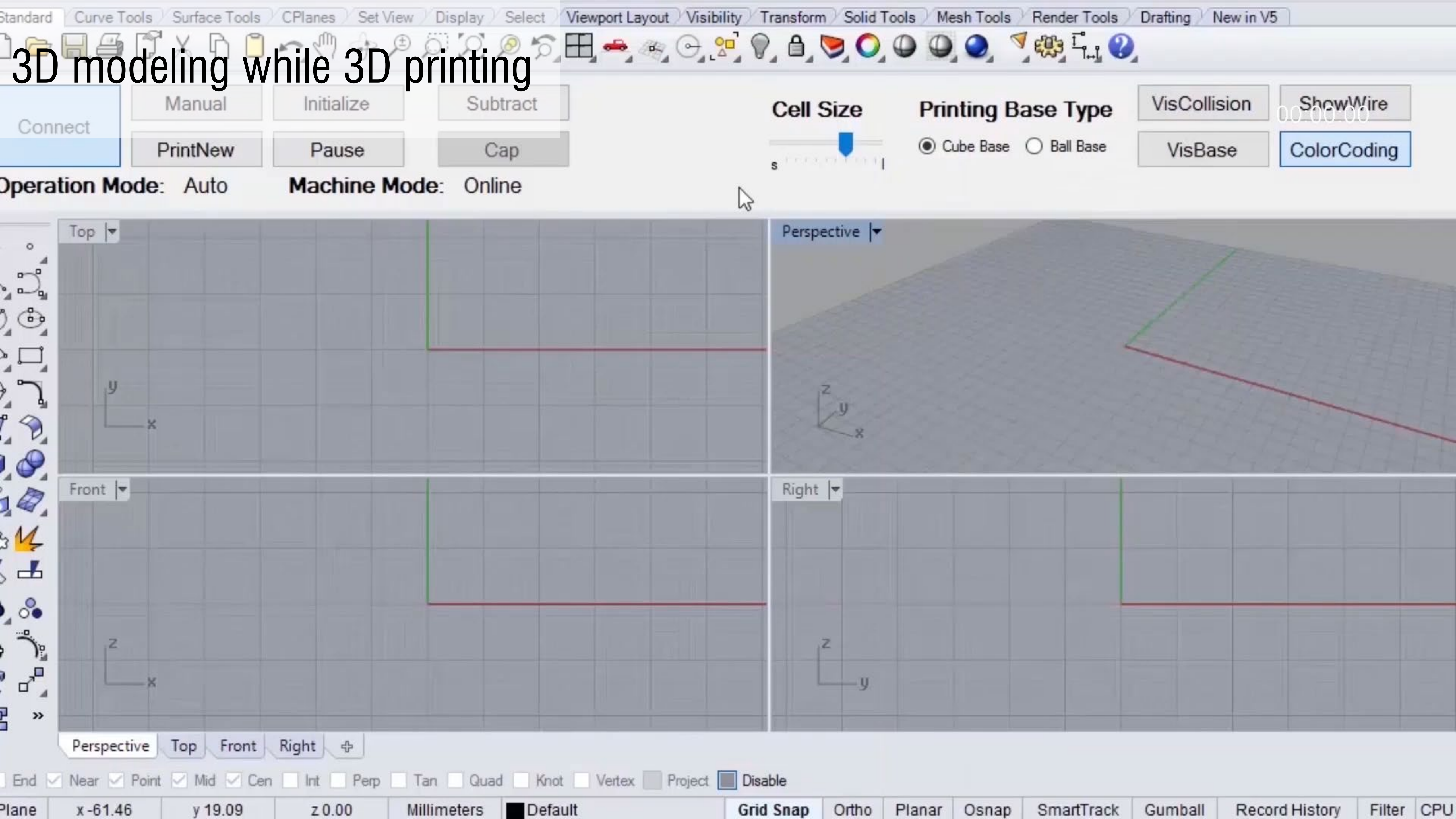
ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): User Interfaces.

INTRODUCTION

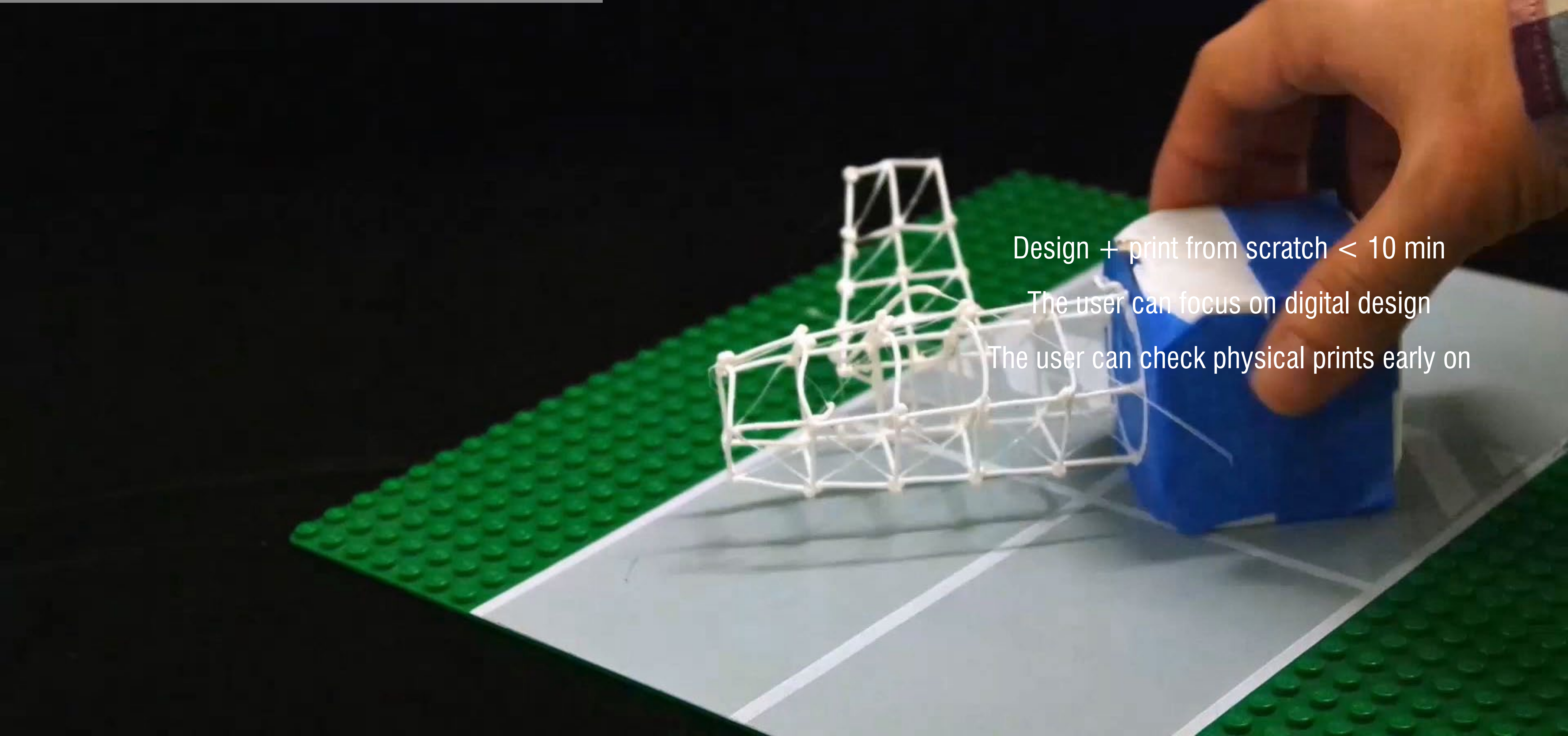
Since the notion of interactive fabrication was introduced by Willis et al. [32], several approaches have been proposed for hands-on digital fabrication. For example, Constructable [17] allows the step-by-step fabrication of functional objects using a laser cutter controlled by a laser pointer; D-Coil [19] enables non-experts to design 3D digital models from scratch using a digitally controlled wax extruder; ReForm [31] merges manual shaping with digital milling and extrusion of synthetic clay. On the one hand, these interactive fabrication systems offer immediate, tangible feedback that can benefit

CHI 16
Peng et.al.

3D modeling while 3D printing



3D modeling while 3D printing

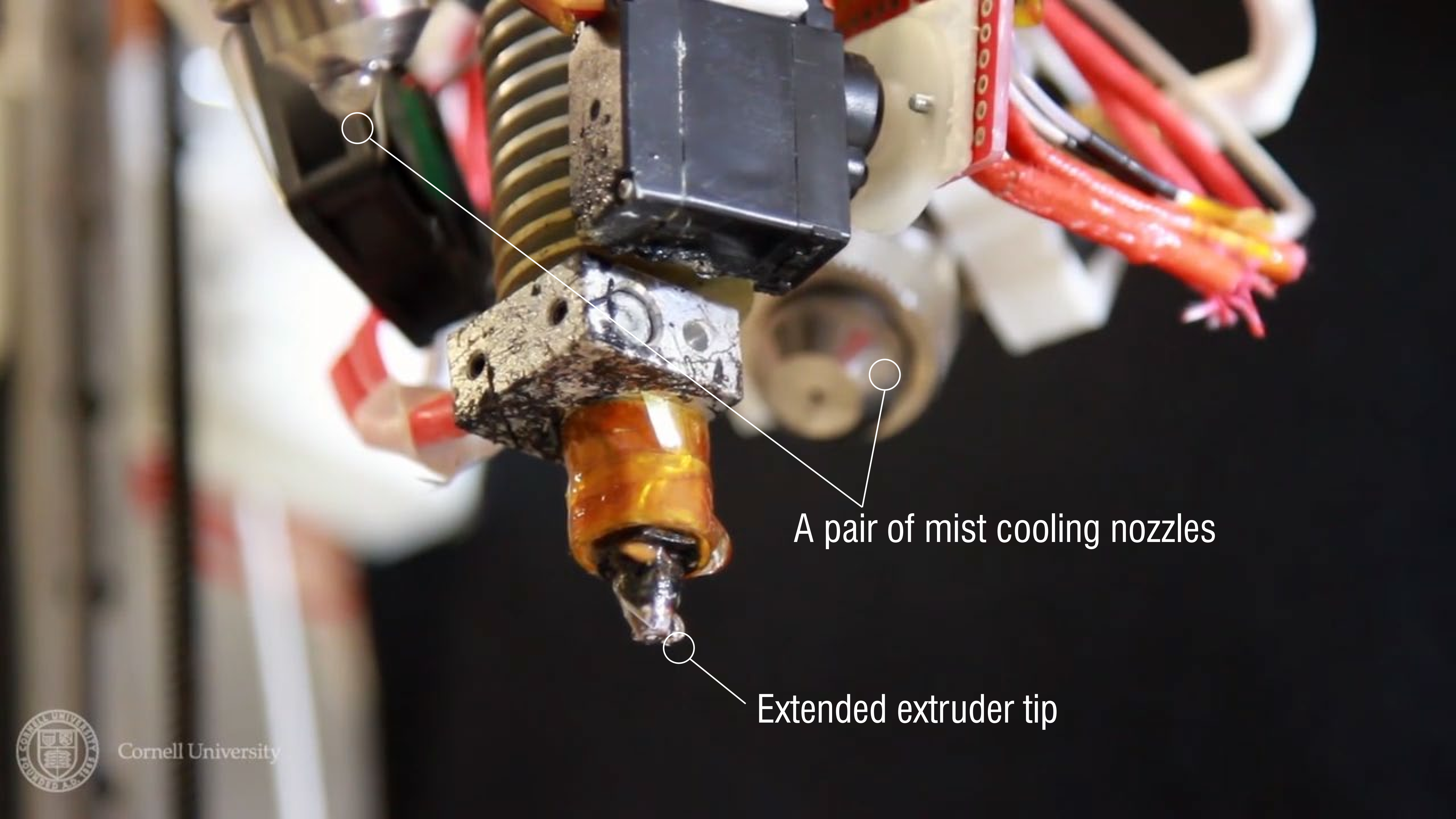


To support design and fab **in parallel**
our machine should be able to

print fast
print incrementally
make subtractive changes

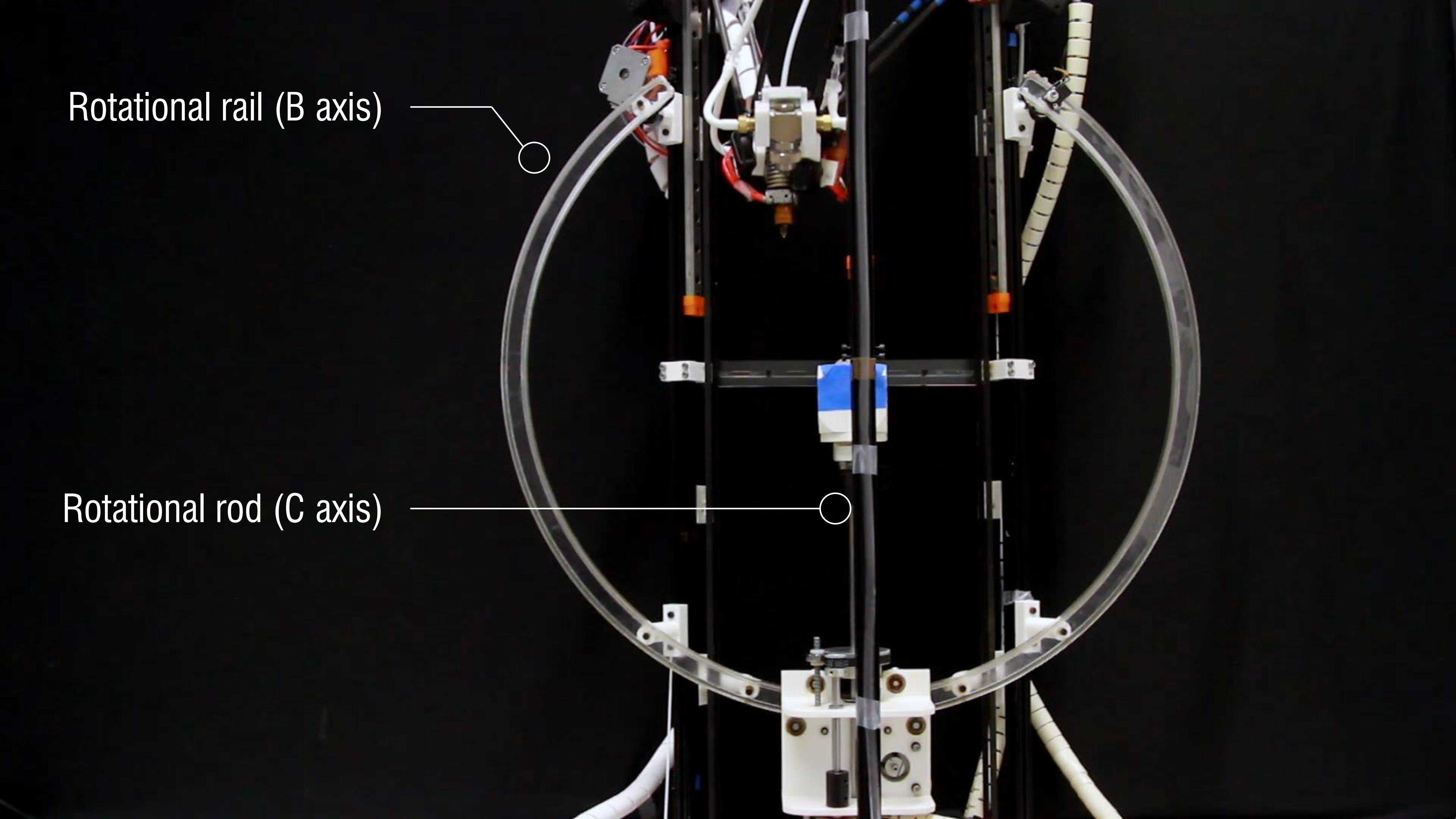
To support design and fab **in parallel**
our machine should be able to

print fast (to catch up the CAD design speed)
print incrementally
make subtractive changes


A pair of mist cooling nozzles
Extended extruder tip
Cornell University

To support design and fab **in parallel**
our machine should be able to

print fast
print incrementally (to avoid reprint every time)
make subtractive changes


Rotational rail (B axis)
Rotational rod (C axis)

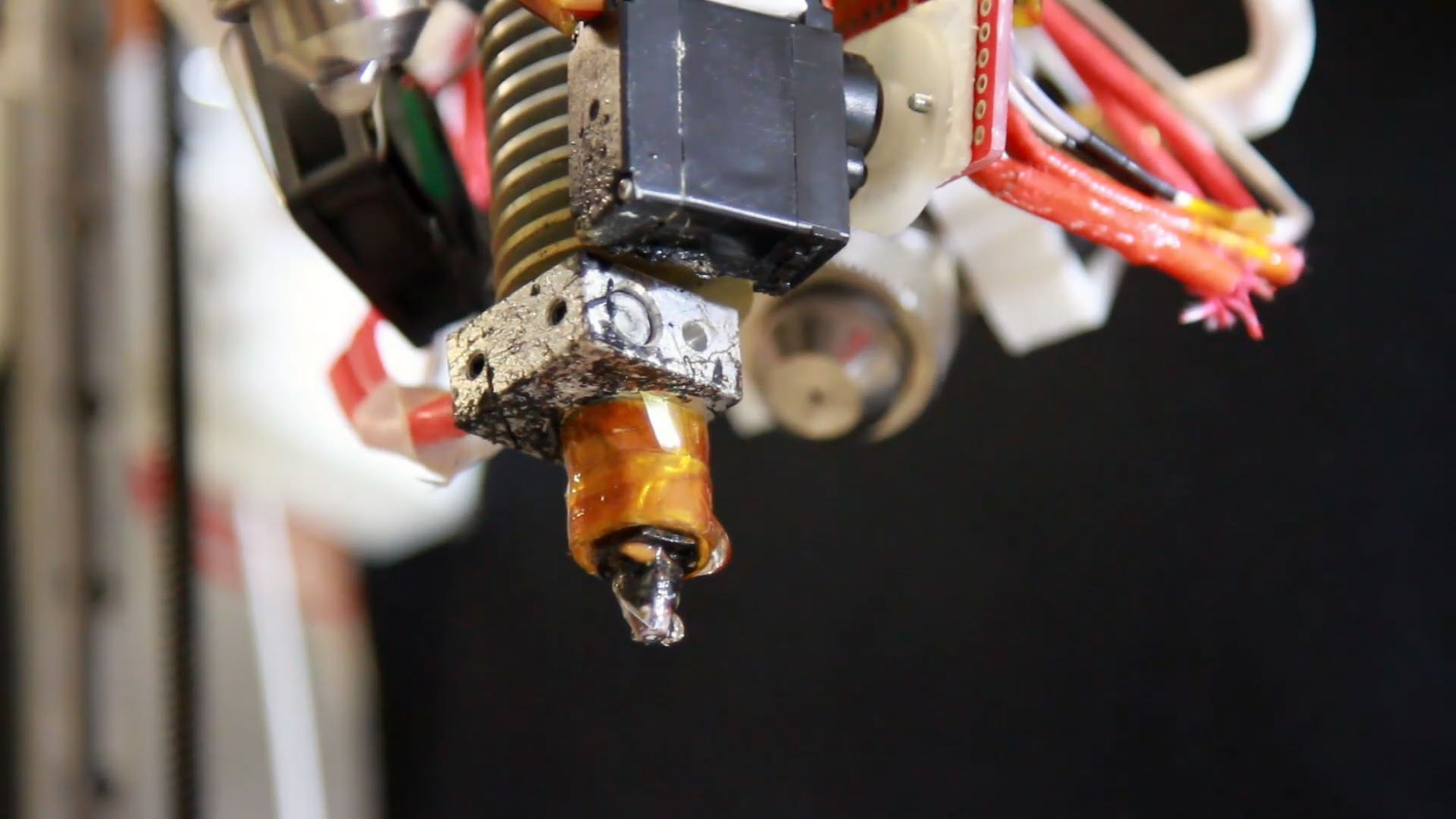
To support design and fab **in parallel**

our machine should be able to

print fast

print incrementally

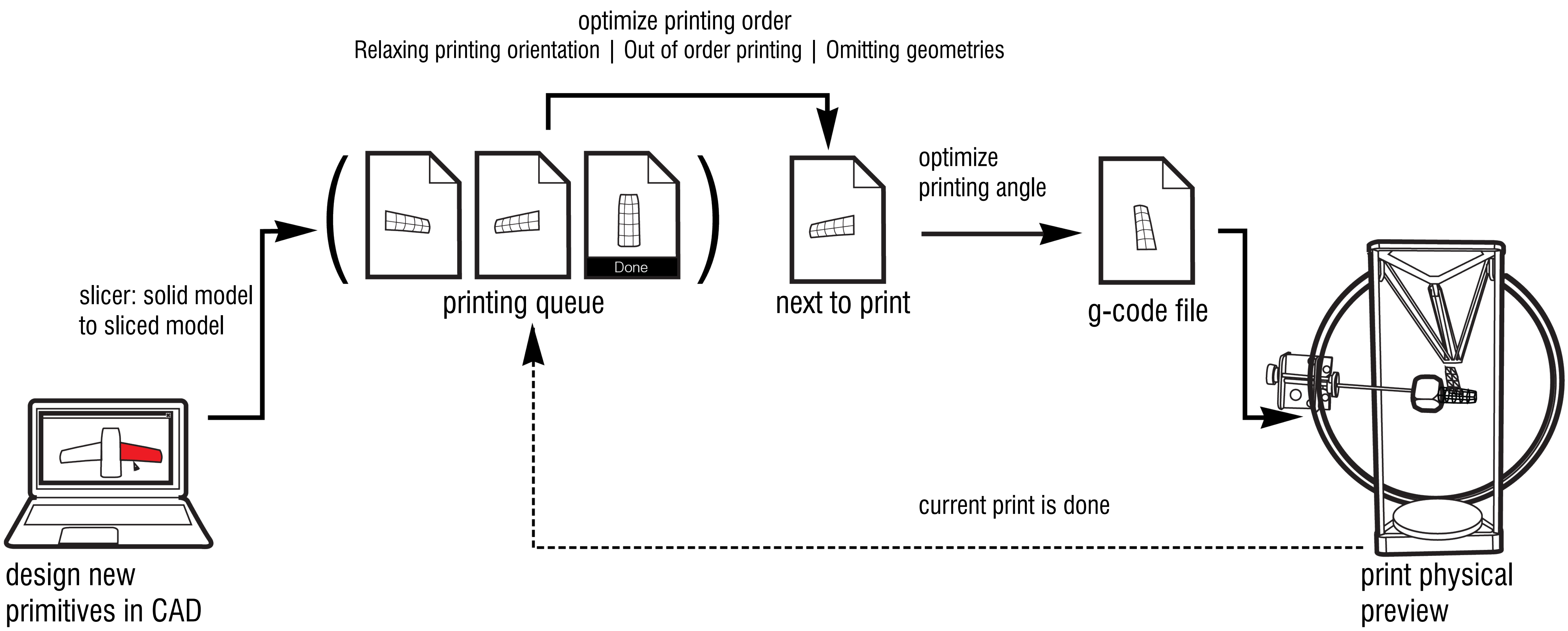
make subtractive changes (to reflect digital editing)

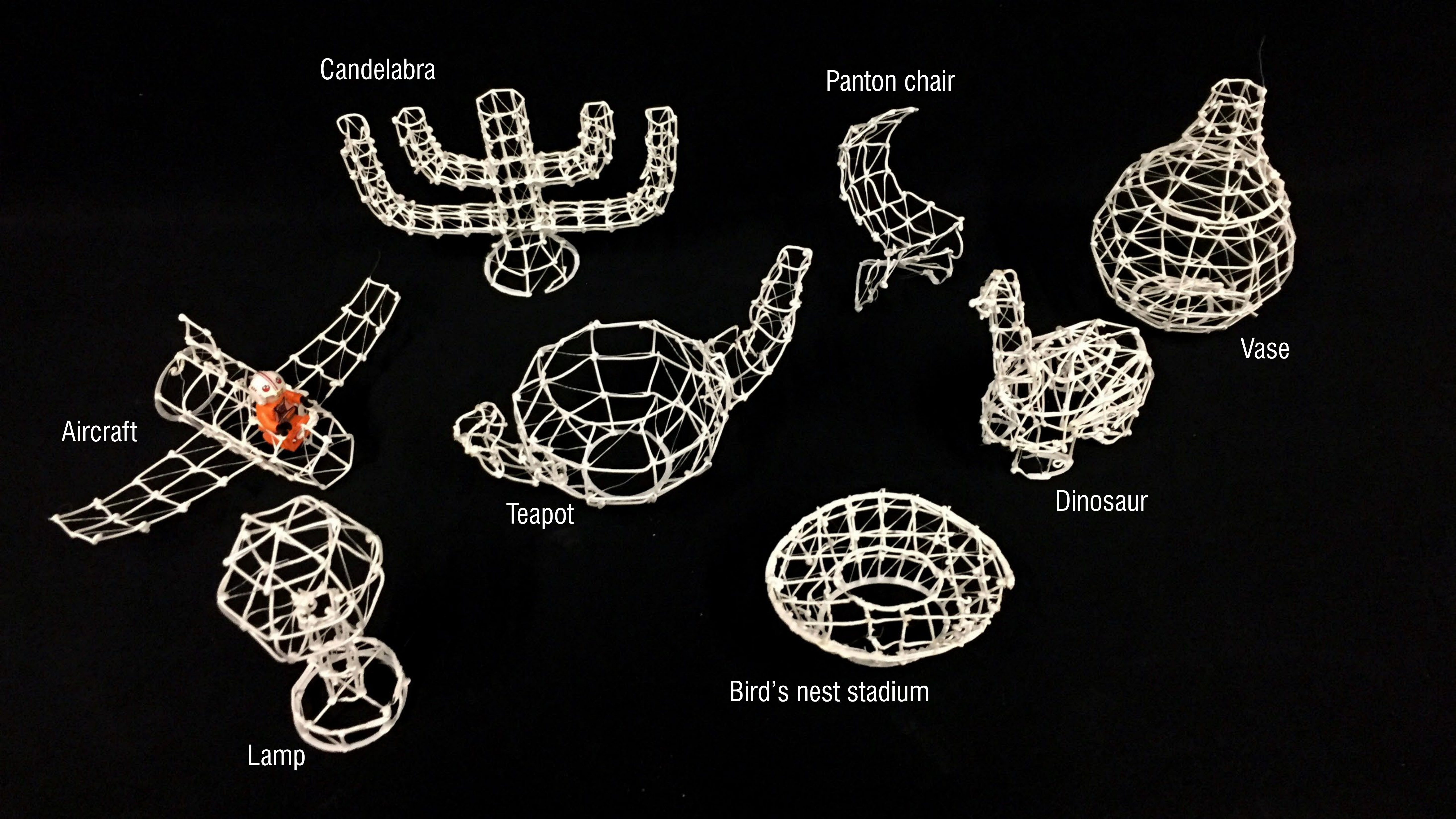


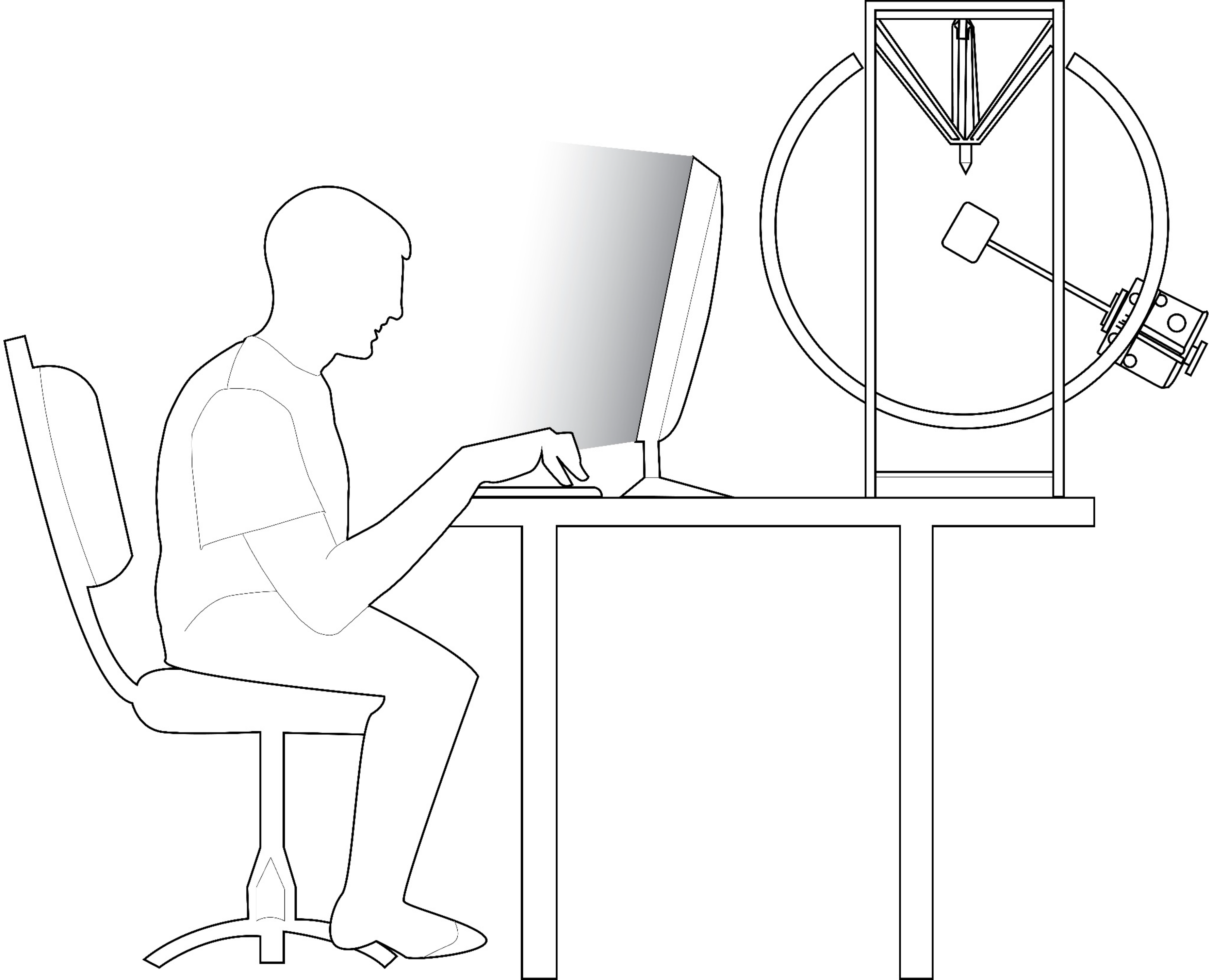
To allow the designer to focus on the design
our software should be able to

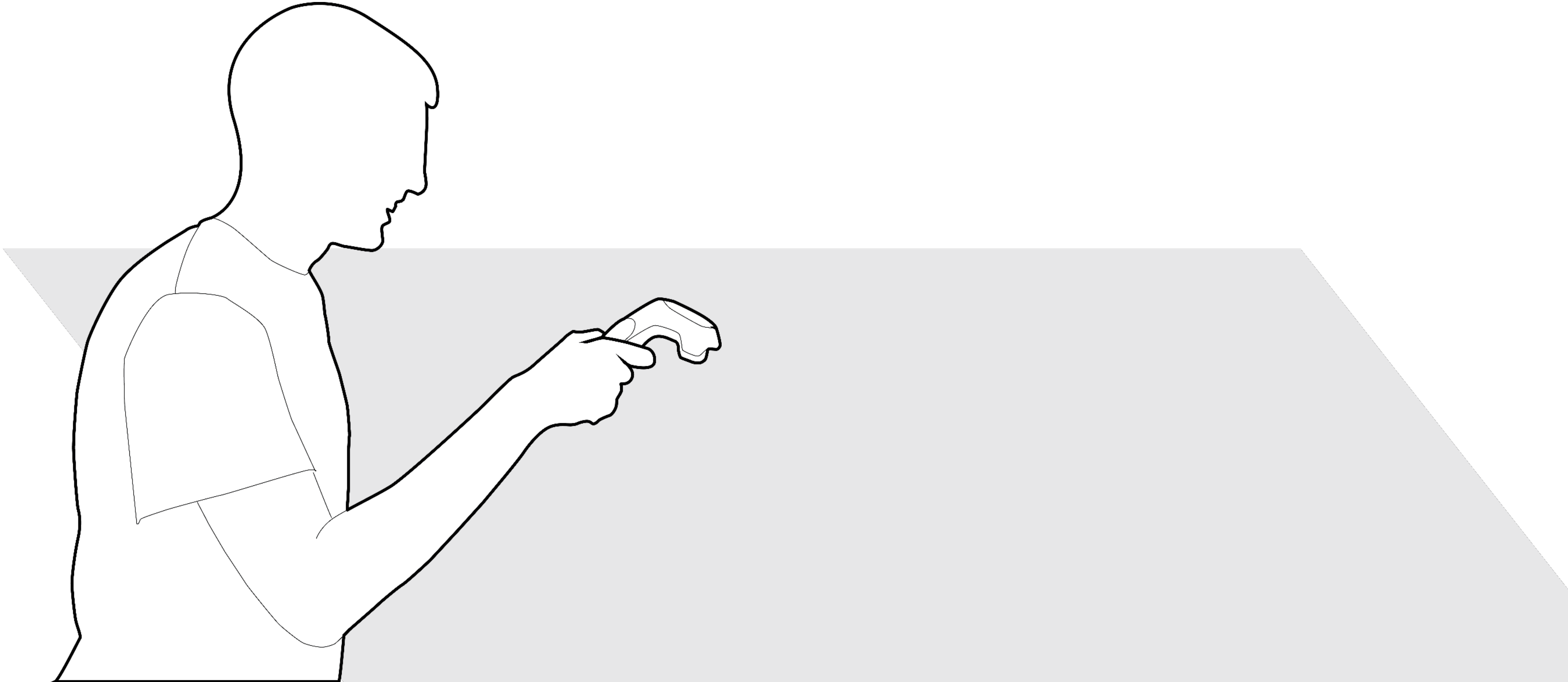
print new primitives automatically
solve potential collisions

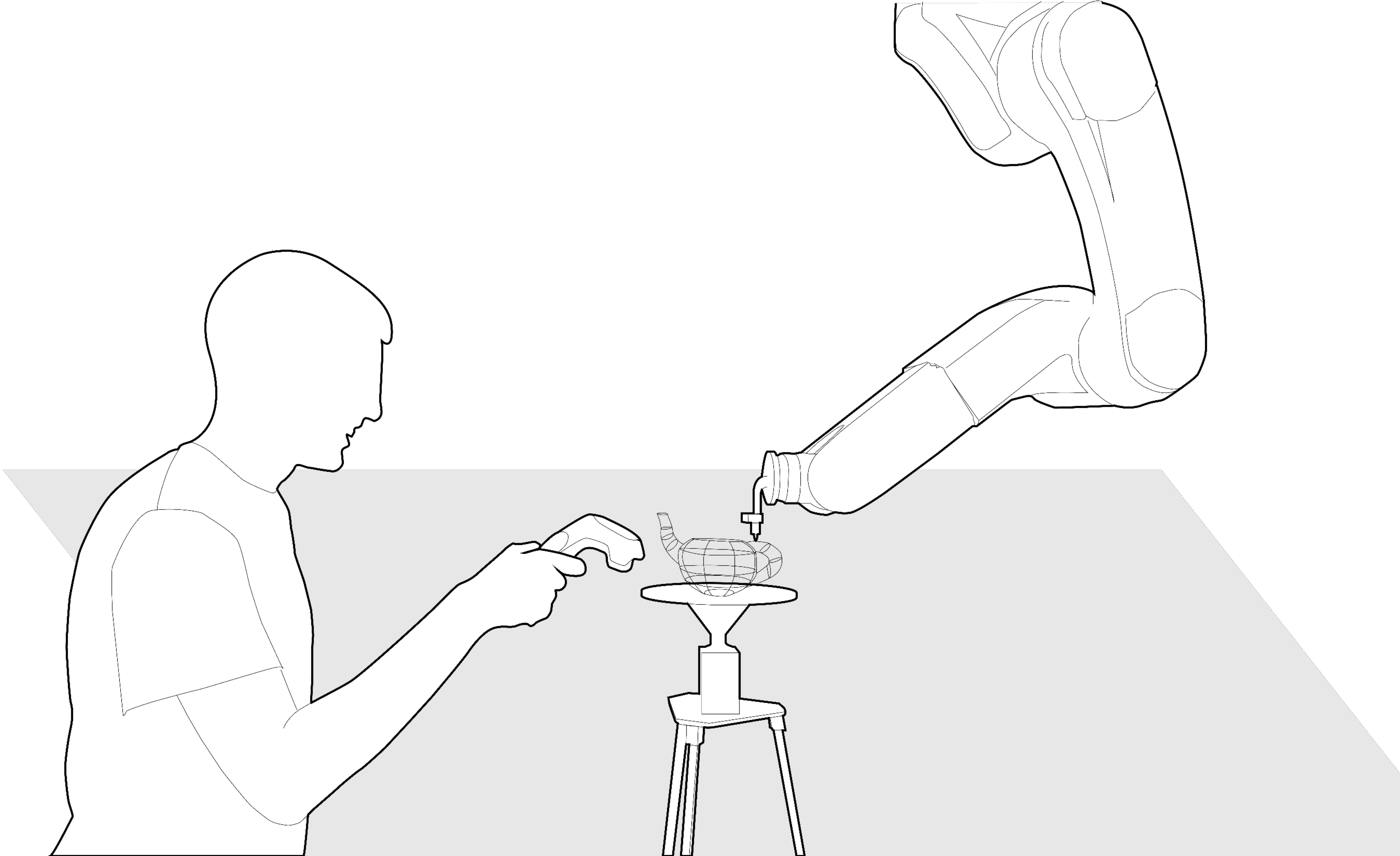
Software Workflow

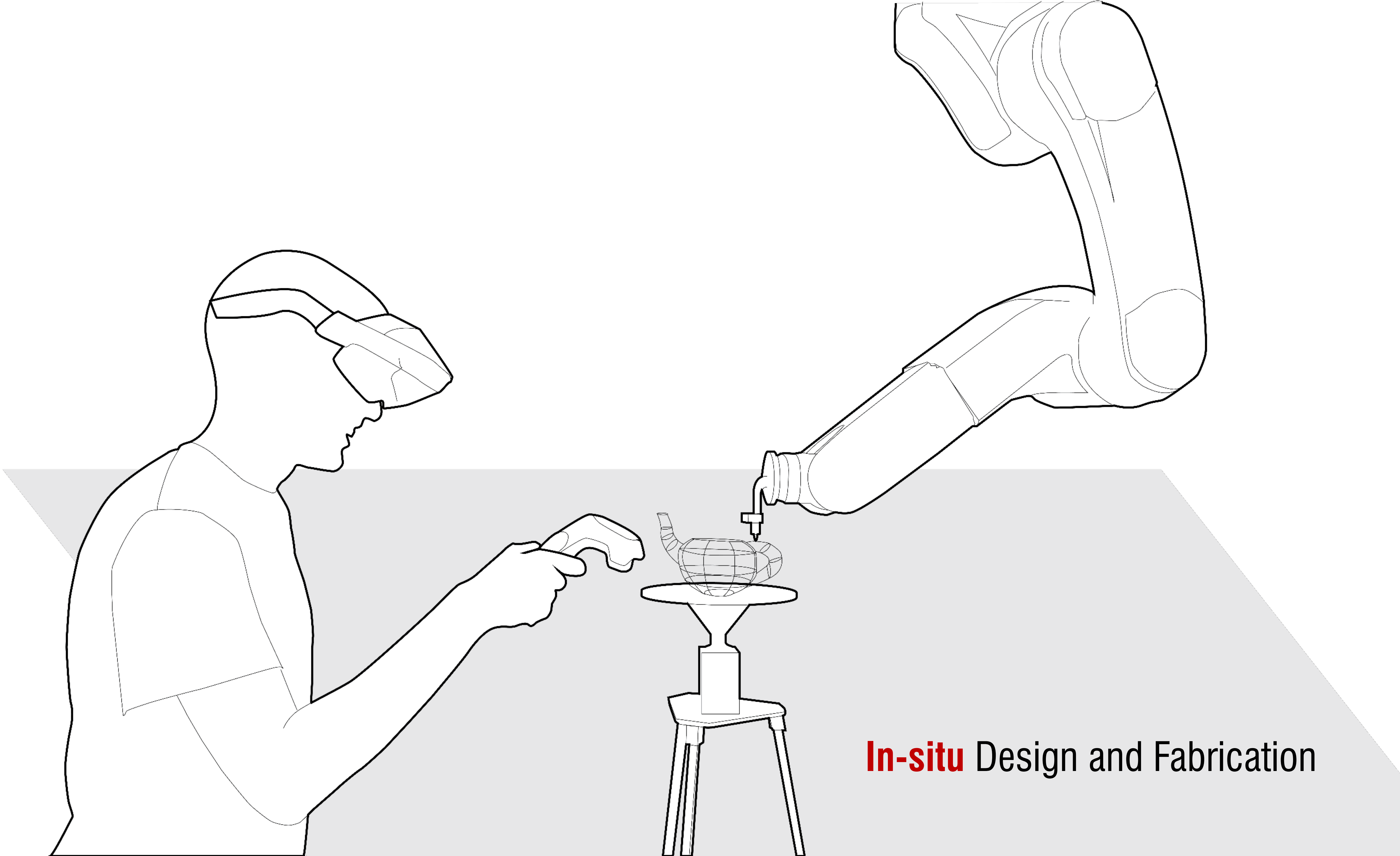



Candelabra
Panton chair
Vase
Aircraft
Teapot
Dinosaur
Bird’s nest stadium
Lamp

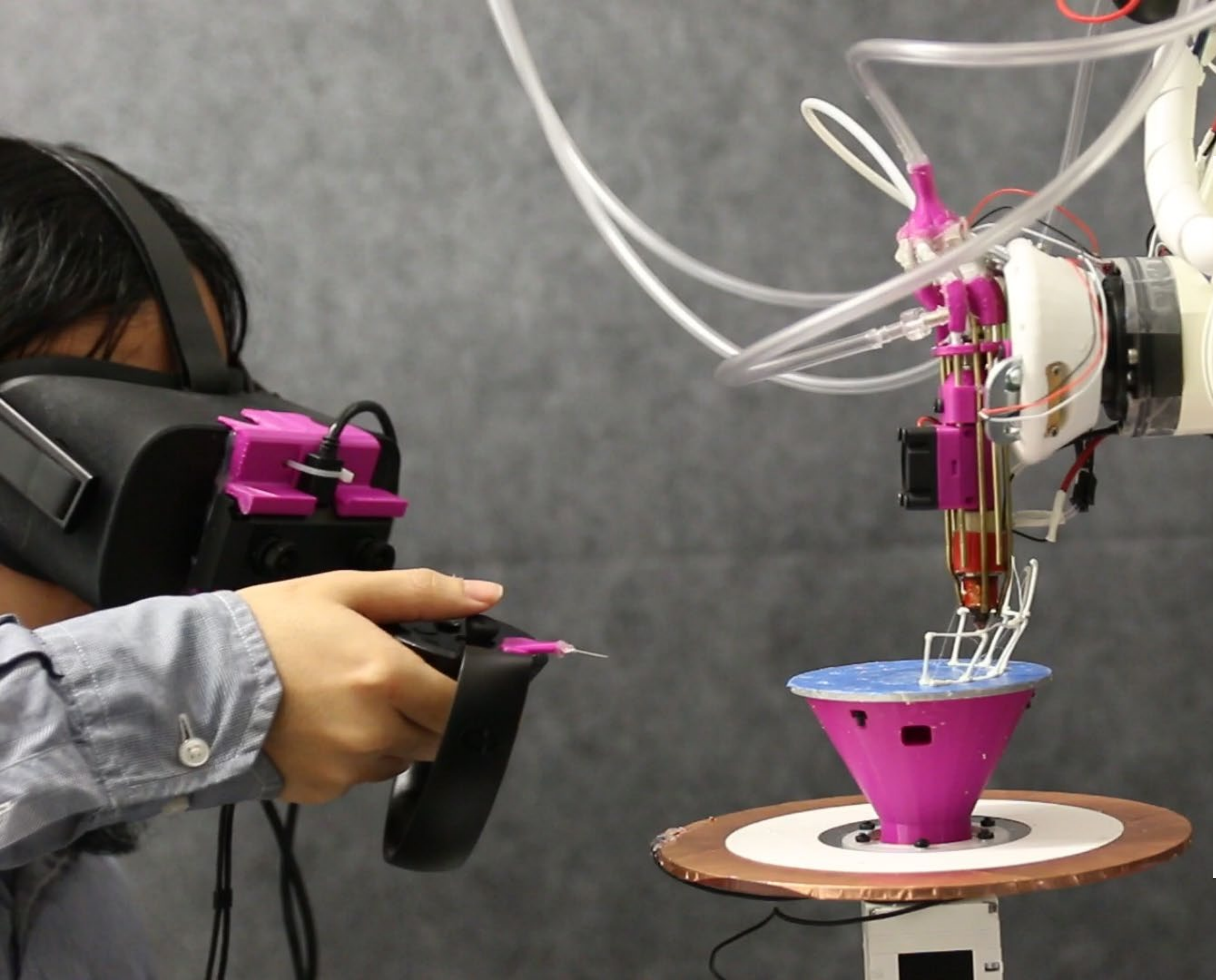


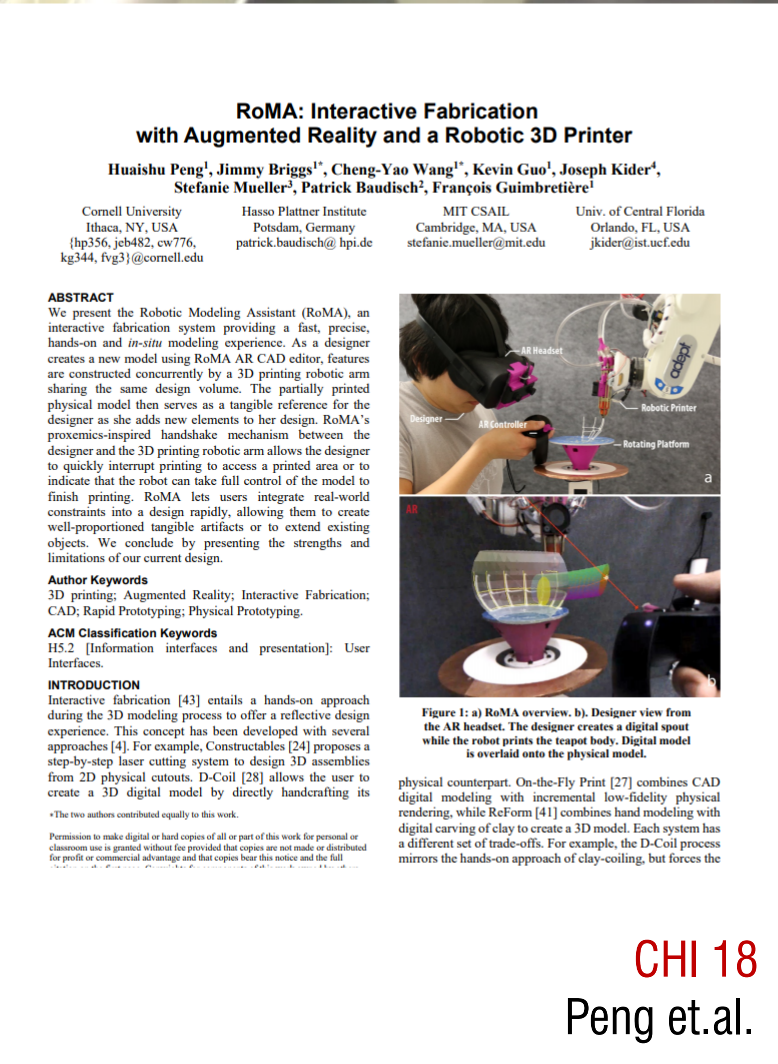






In-situ Design and Fabrication





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.

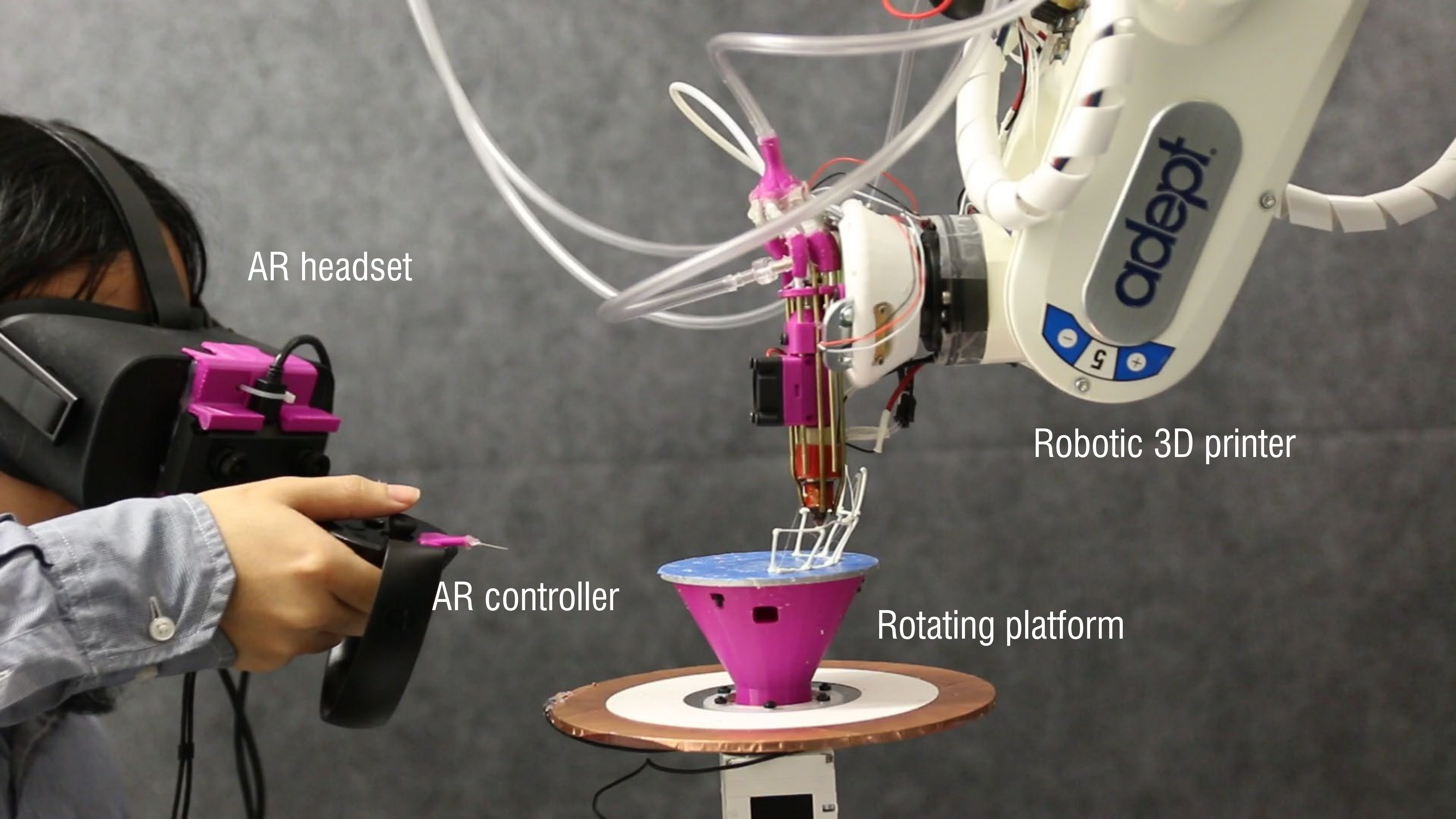
INTRODUCTION
Interactive fabrication [43] entails a hands-on approach during the 3D modeling process to offer a reflective design experience. This concept has been developed with several approaches [4]. For example, Constructables [24] proposes a step-by-step laser cutting system to design 3D assemblies from 2D physical cutouts. D-Coil [28] allows the user to create a 3D digital model by directly handcrafting its

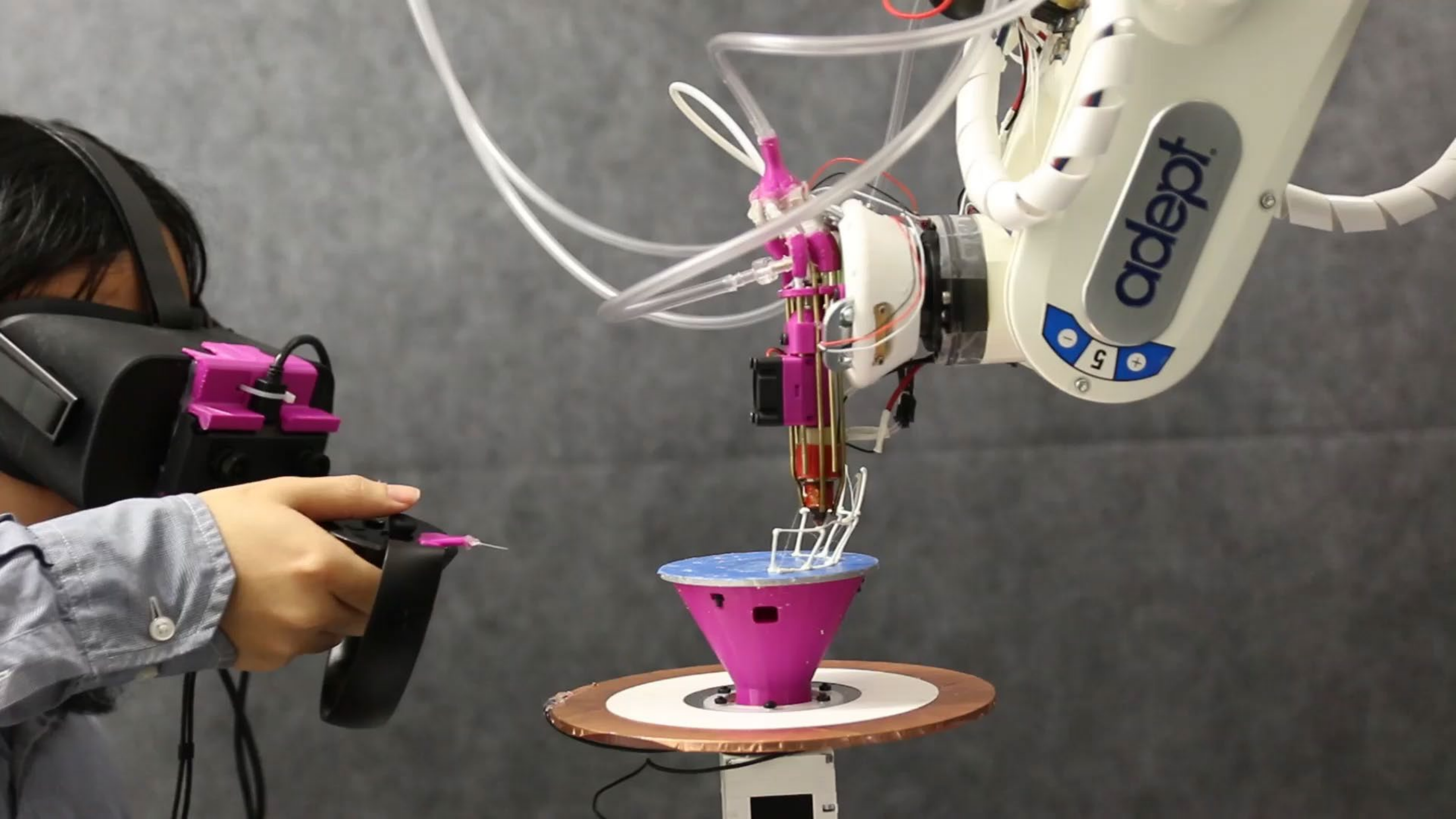
Figure 1: a) RoMA overview. b). Designer view from the AR headset. The designer creates a digital spout while the robot prints the teapot body. Digital model is overlaid onto the physical model.

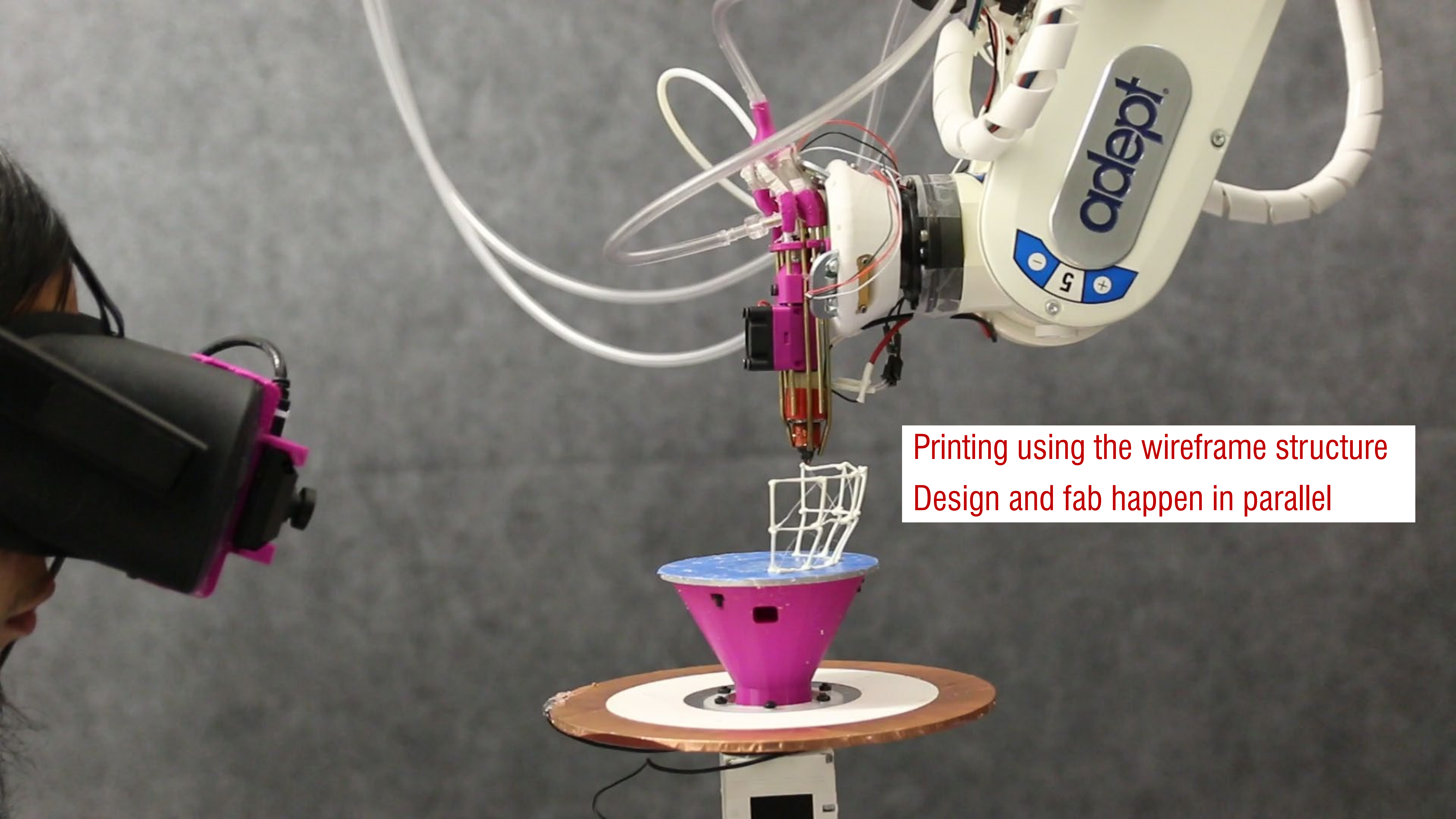
physical counterpart. On-the-Fly Print [27] combines CAD digital modeling with incremental low-fidelity physical rendering, while ReForm [41] combines hand modeling with digital carving of clay to create a 3D model. Each system has a different set of trade-offs. For example, the D-Coil process mirrors the hands-on approach of clay-coiling, but forces the

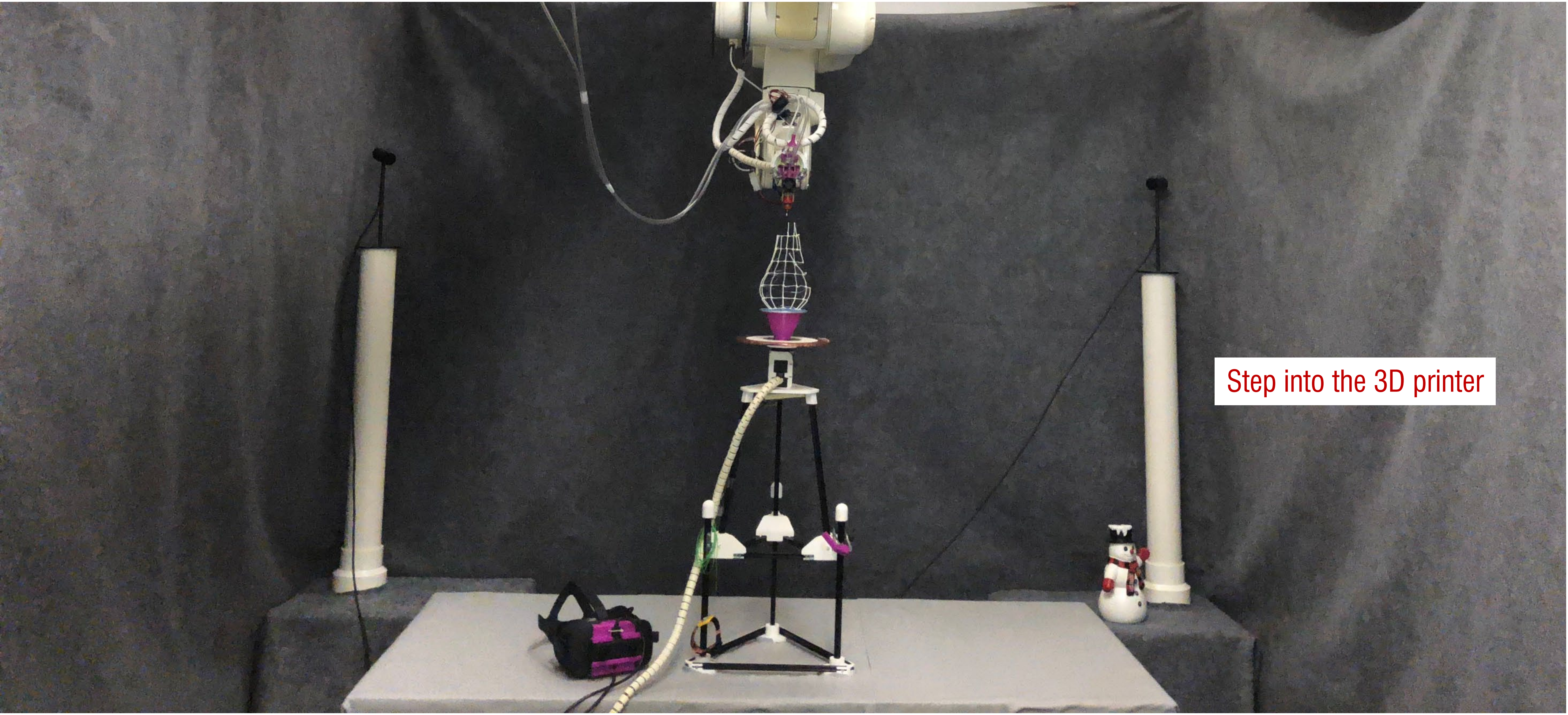
*The two authors contributed equally to this work.

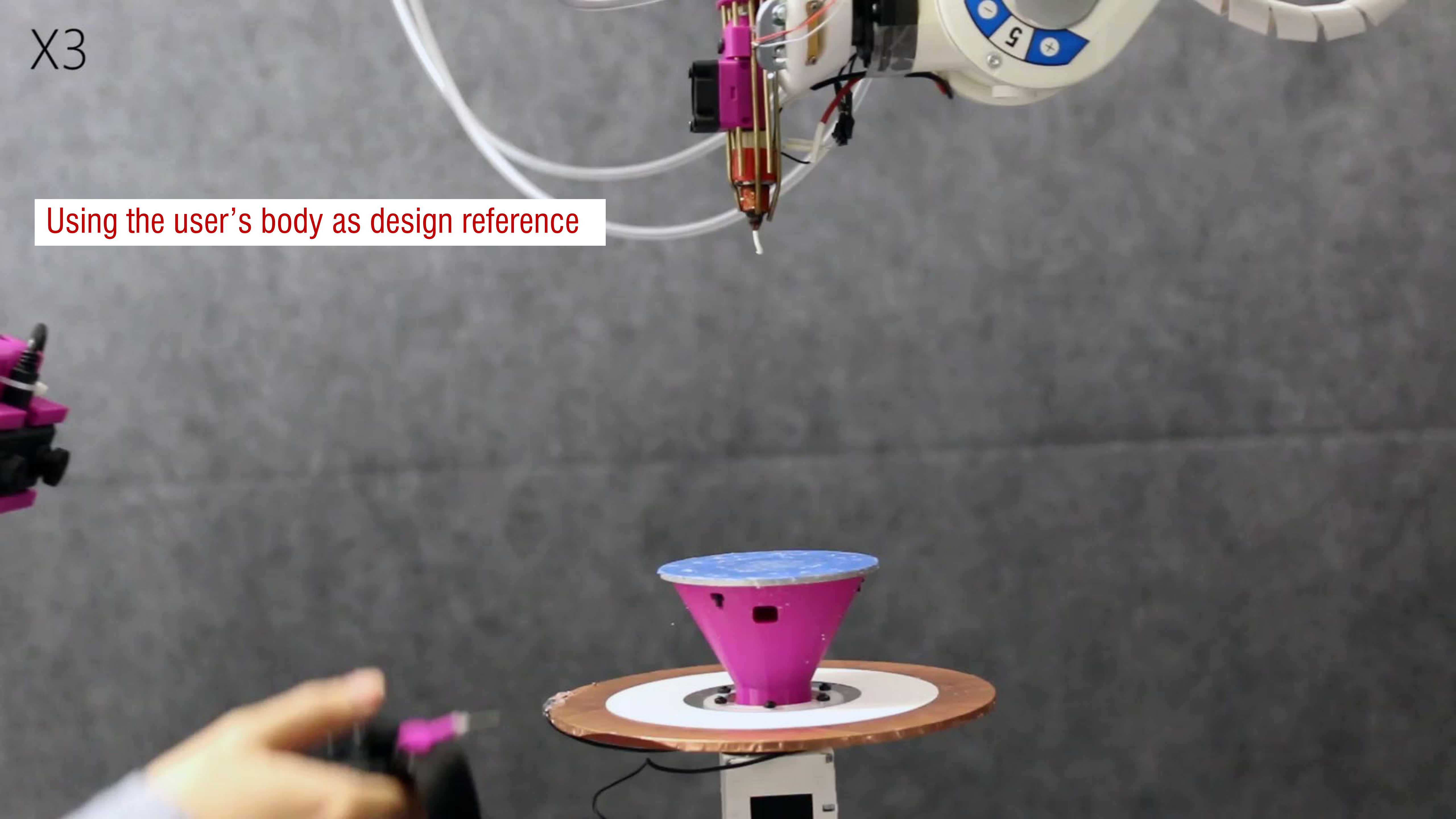
CHI 18
Peng et.al.

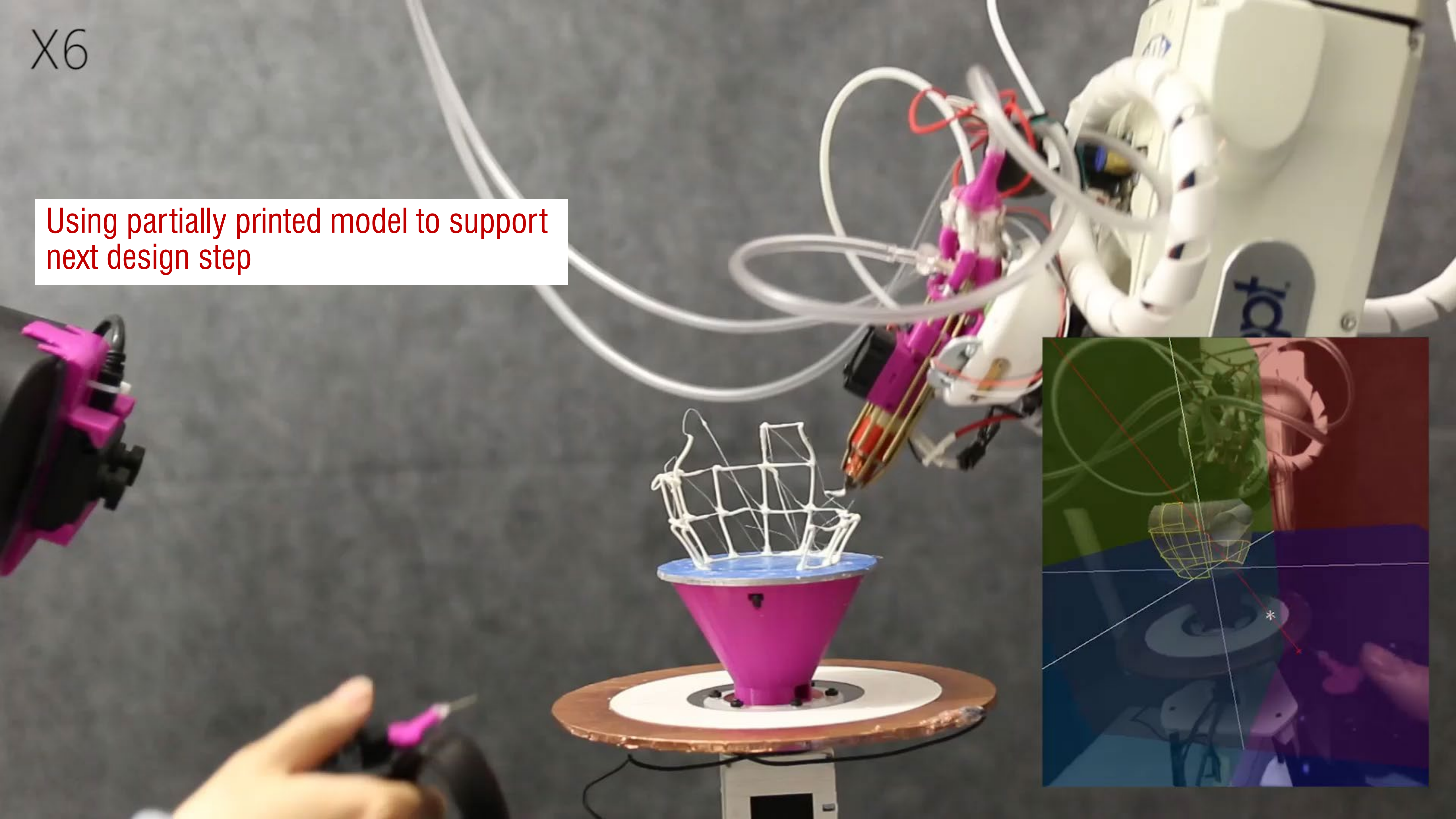

AR headset
Robotic 3D printer
AR controller
Rotating platform
adept


adept
5


adept
Printing using the wireframe structure
Design and fab happen in parallel

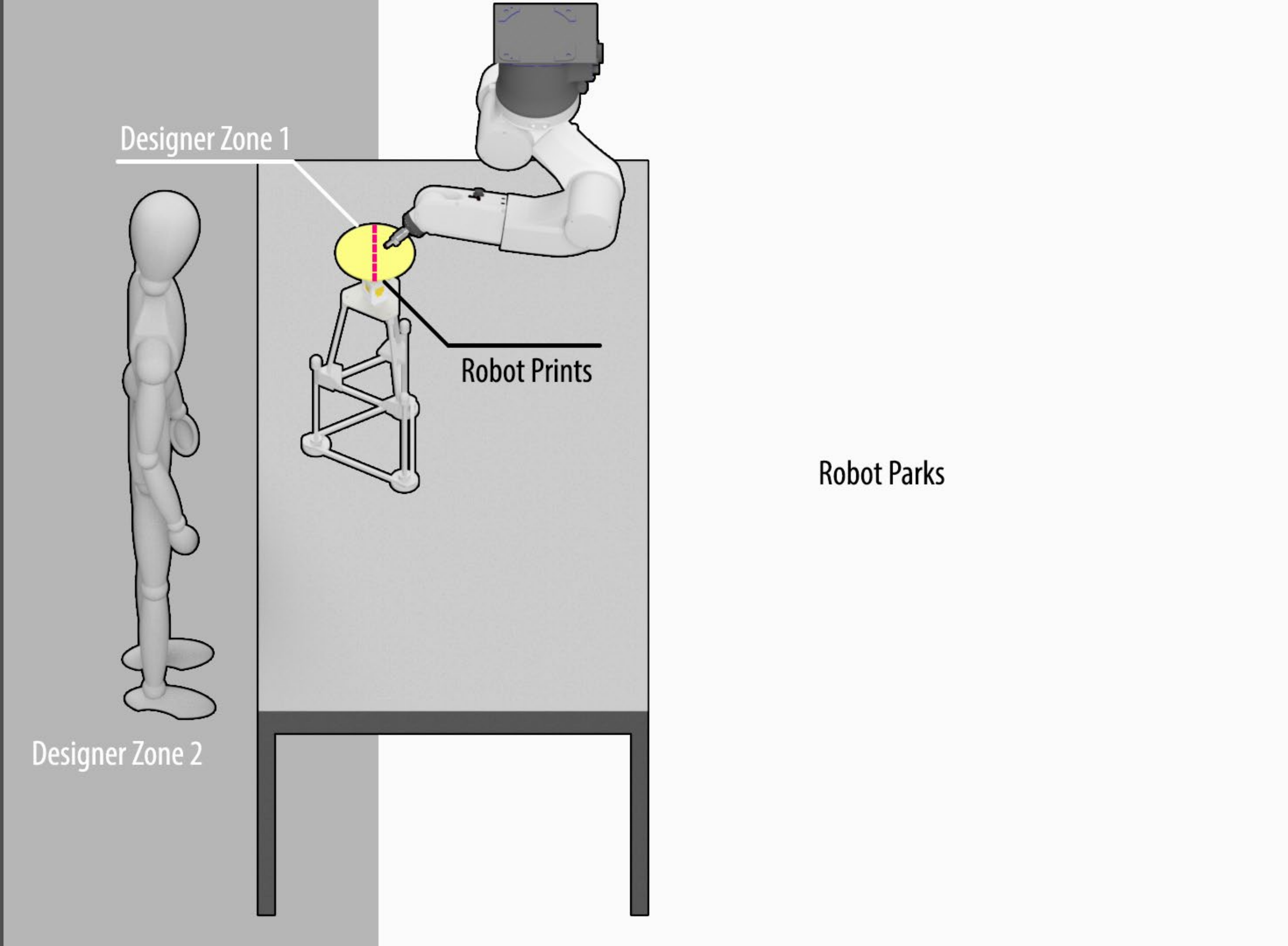

Step into the 3D printer

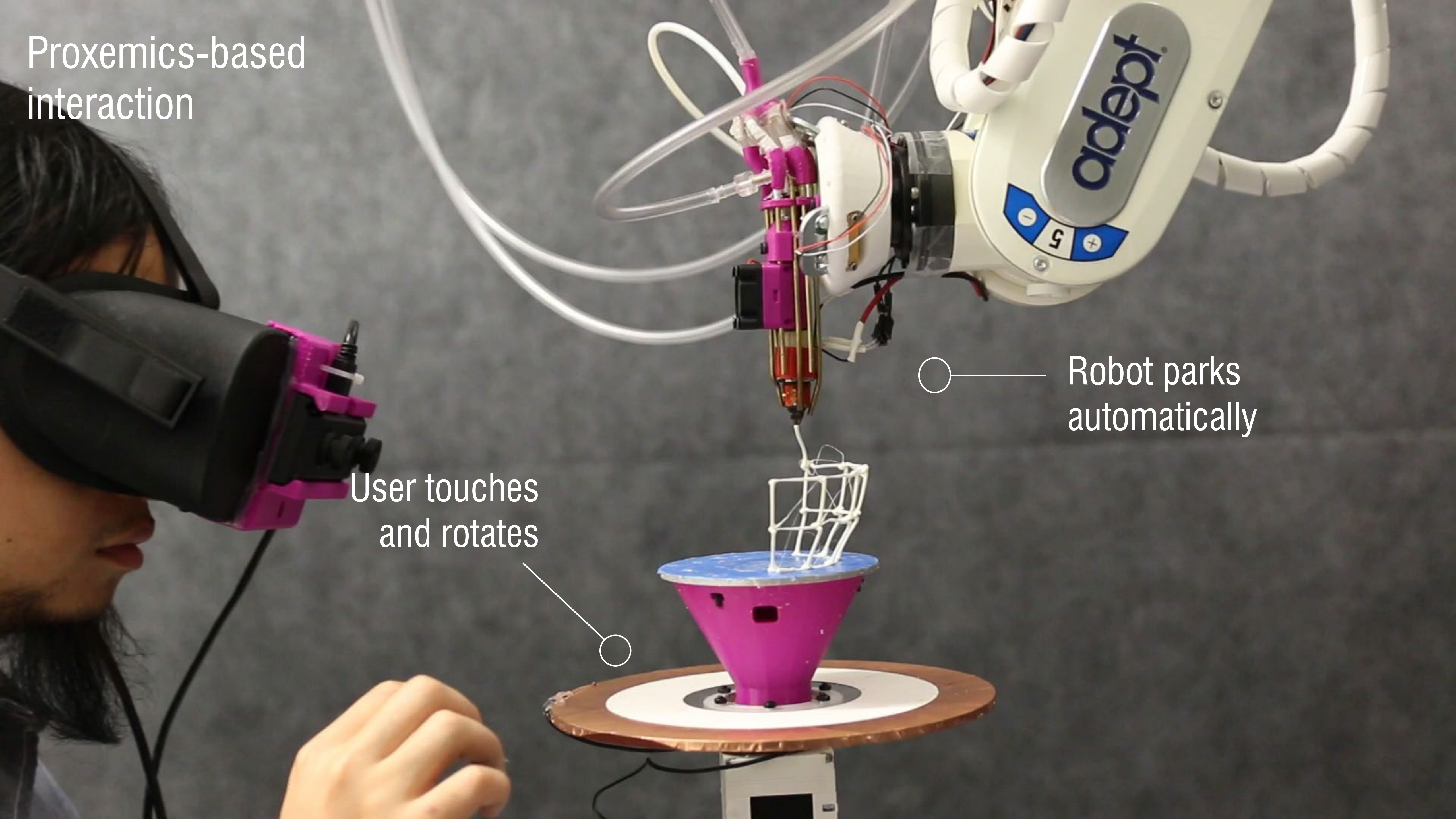

X3
Using the user’s body as design reference

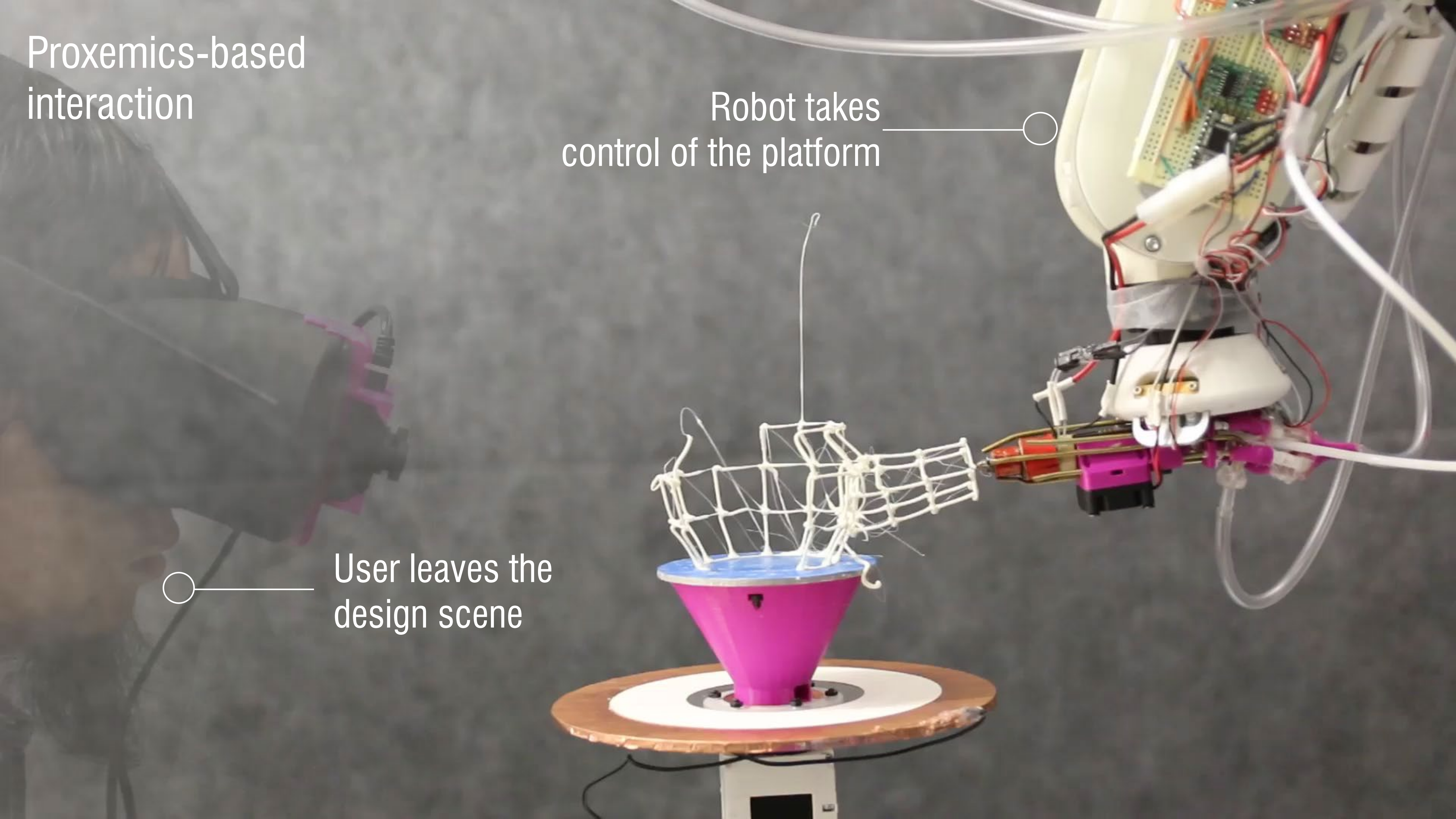

X6
Using partially printed model to support next design step

Design and fabrication directly
ON a physical object

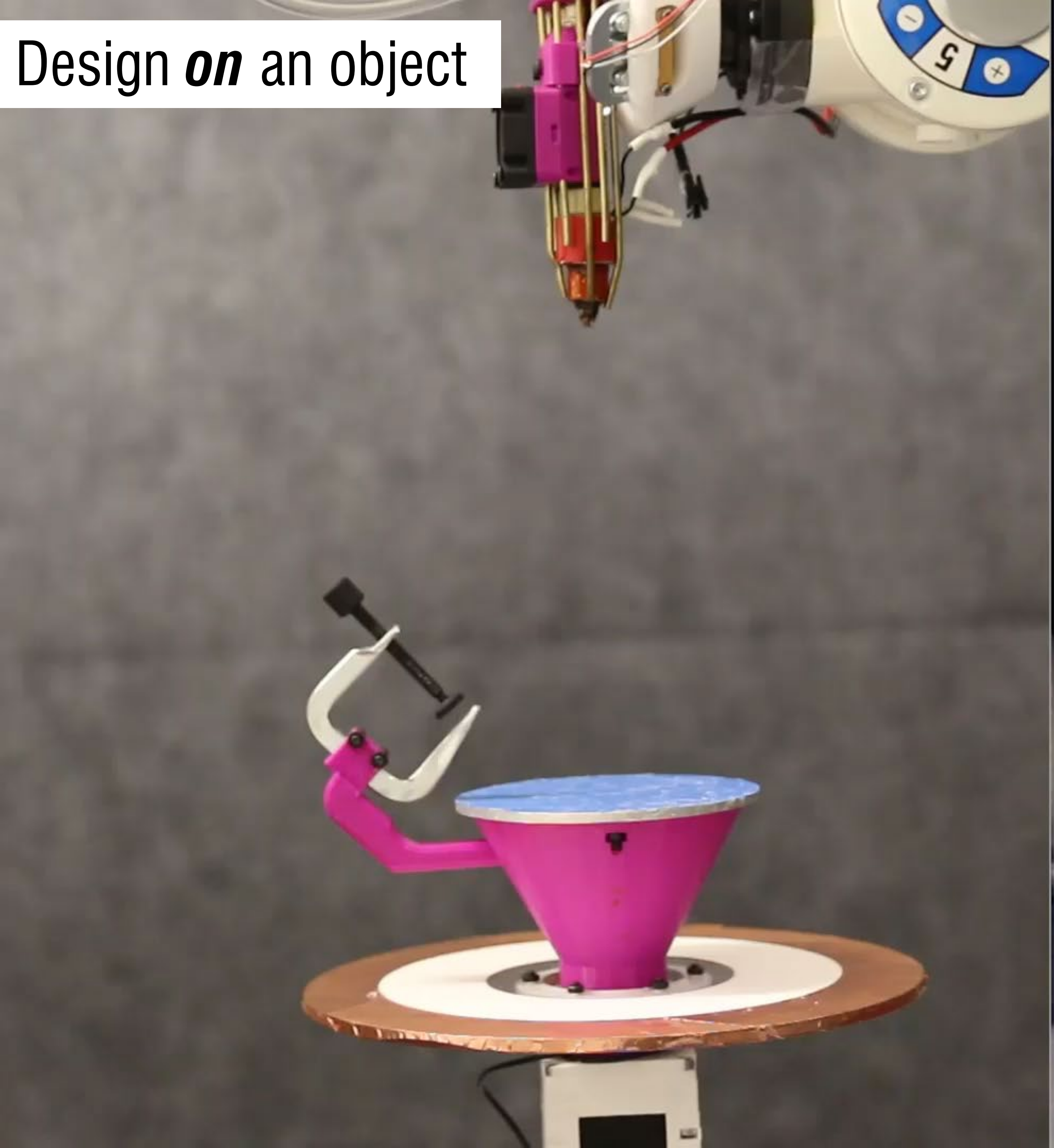
Proxemics-based interaction

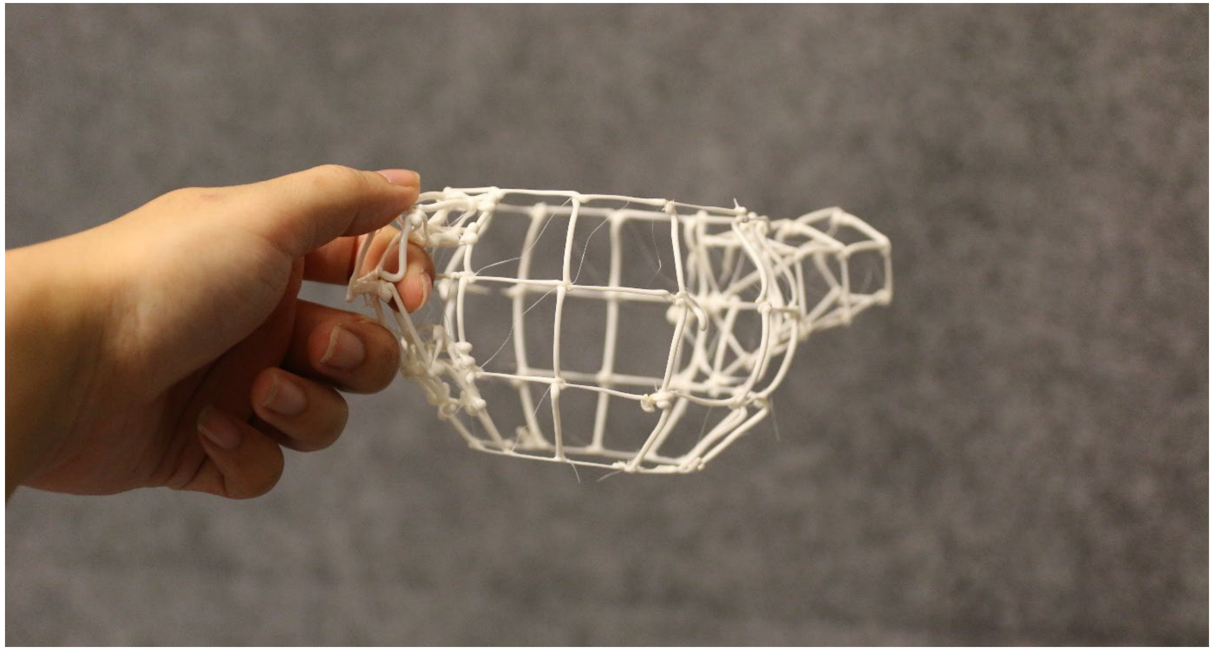



Proxemics-based
interaction
Robot parks
automatically
User touches
and rotates
adept


Proxemics-based
interaction
Robot takes
control of the platform
User leaves the
design scene

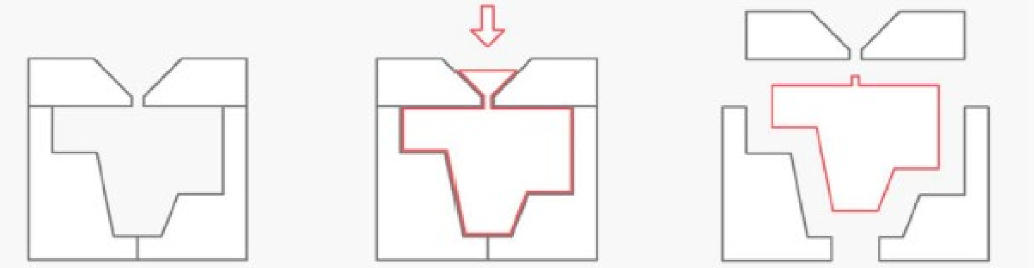
Design ***on*** an object



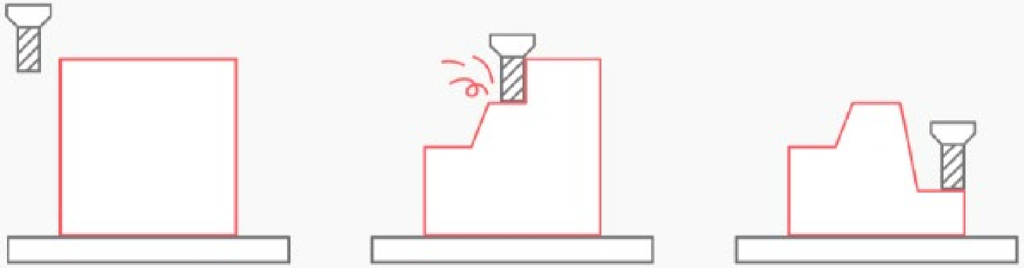



Adding and removing material is still very slow

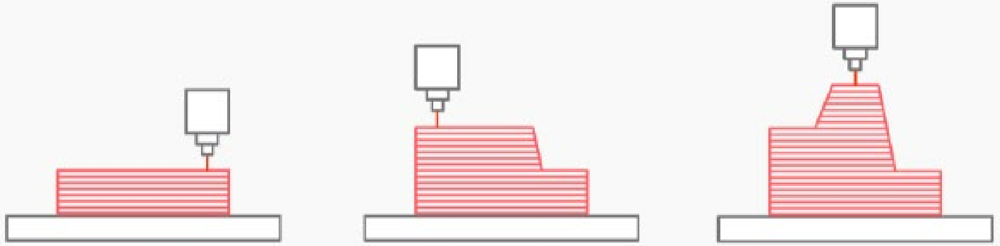
Can we **directly reshape** the material?



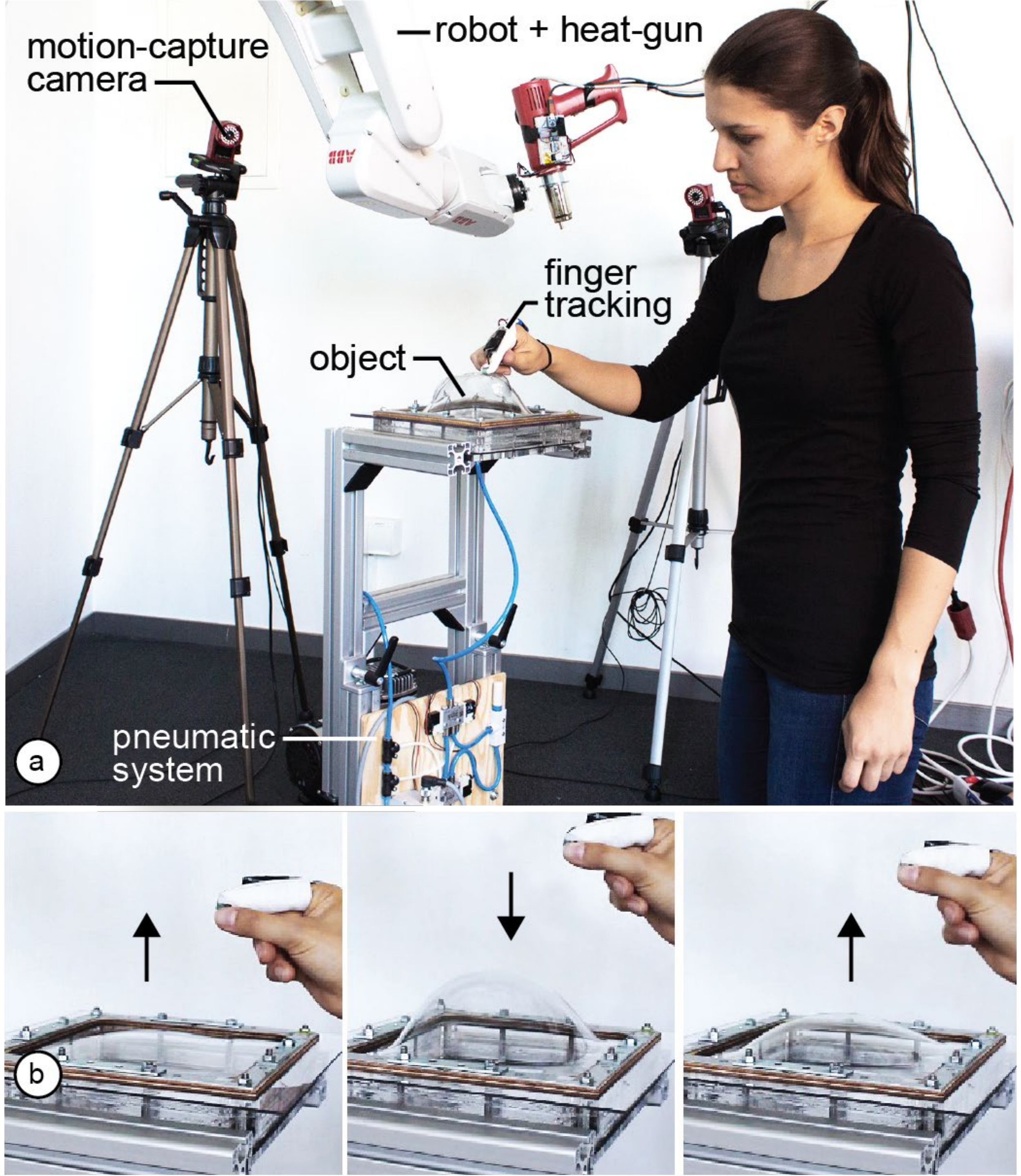
Formative manufacturing

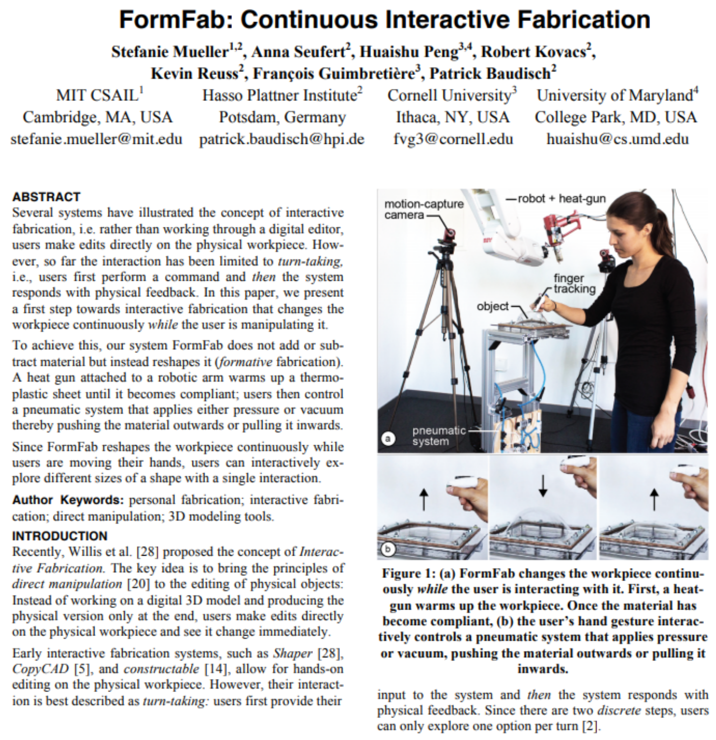


Subtractive manufacturing



Additive manufacturing





FormFab: Continuous Interactive Fabrication

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ABSTRACT

Several systems have illustrated the concept of interactive fabrication, i.e. rather than working through a digital editor, users make edits directly on the physical workpiece. However, so far the interaction has been limited to *turn-taking*, i.e., users first perform a command and *then* the system responds with physical feedback. In this paper, we present a first step towards interactive fabrication that changes the workpiece continuously *while* the user is manipulating it.

To achieve this, our system FormFab does not add or subtract material but instead reshapes it (*formative* fabrication). A heat gun attached to a robotic arm warms up a thermoplastic sheet until it becomes compliant; users then control a pneumatic system that applies either pressure or vacuum thereby pushing the material outwards or pulling it inwards.

Since FormFab reshapes the workpiece continuously while users are moving their hands, users can interactively explore different sizes of a shape with a single interaction.

Author Keywords: personal fabrication; interactive fabrication; direct manipulation; 3D modeling tools.

INTRODUCTION

Recently, Willis et al. [28] proposed the concept of *Interactive Fabrication*. The key idea is to bring the principles of *direct manipulation* [20] to the editing of physical objects: Instead of working on a digital 3D model and producing the physical version only at the end, users make edits directly on the physical workpiece and see it change immediately.

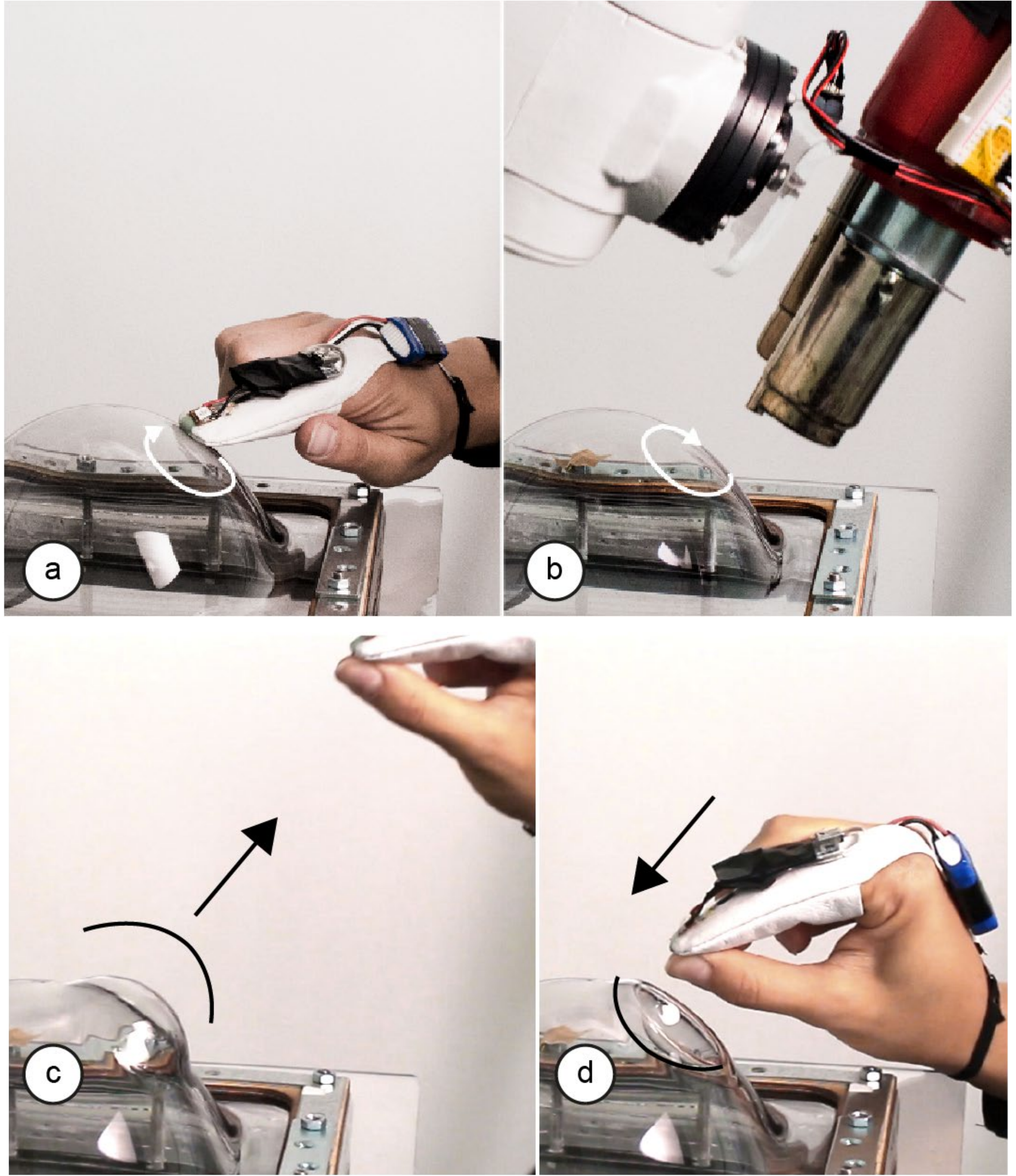
Early interactive fabrication systems, such as *Shaper* [28], *CopyCAD* [5], and *constructable* [14], allow for hands-on editing on the physical workpiece. However, their interaction is best described as *turn-taking:* users first provide their input to the system and *then* the system responds with physical feedback. Since there are two *discrete* steps, users can only explore one option per turn [2].

Figure 1: (a) FormFab changes the workpiece continuously *while* the user is interacting with it. First, a heat-gun warms up the workpiece. Once the material has become compliant, (b) the user's hand gesture interactively controls a pneumatic system that applies pressure or vacuum, pushing the material outwards or pulling it inwards.

TEI 19
Mueller et.al.

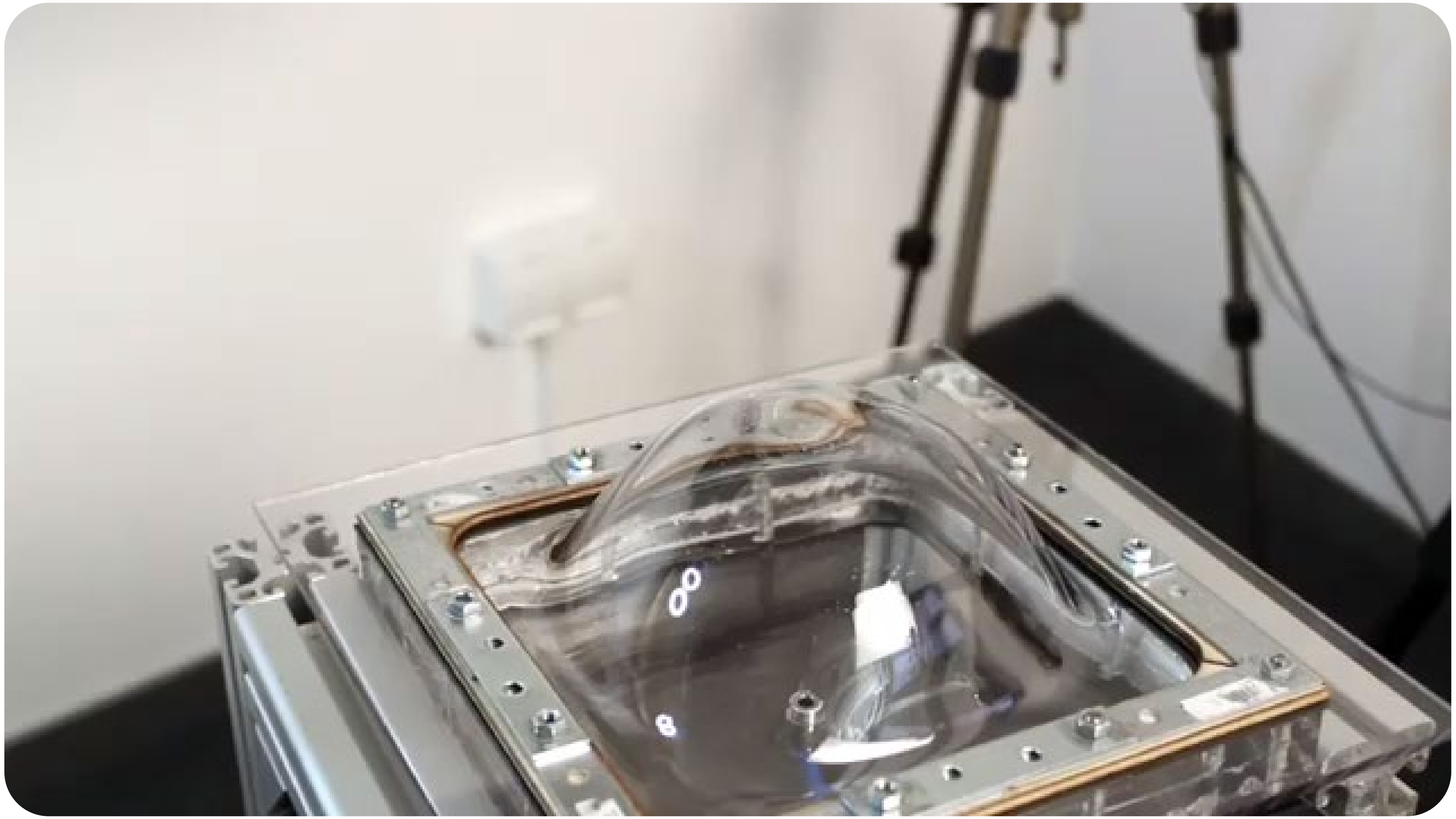
Selectively heat the material

Directly manipulating the area with gestures



Limitations

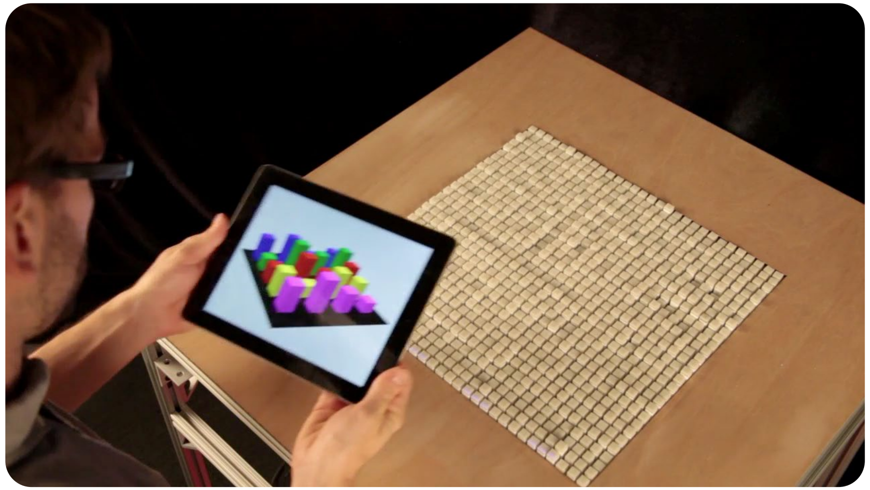
Slow heating process
Limited expressiveness



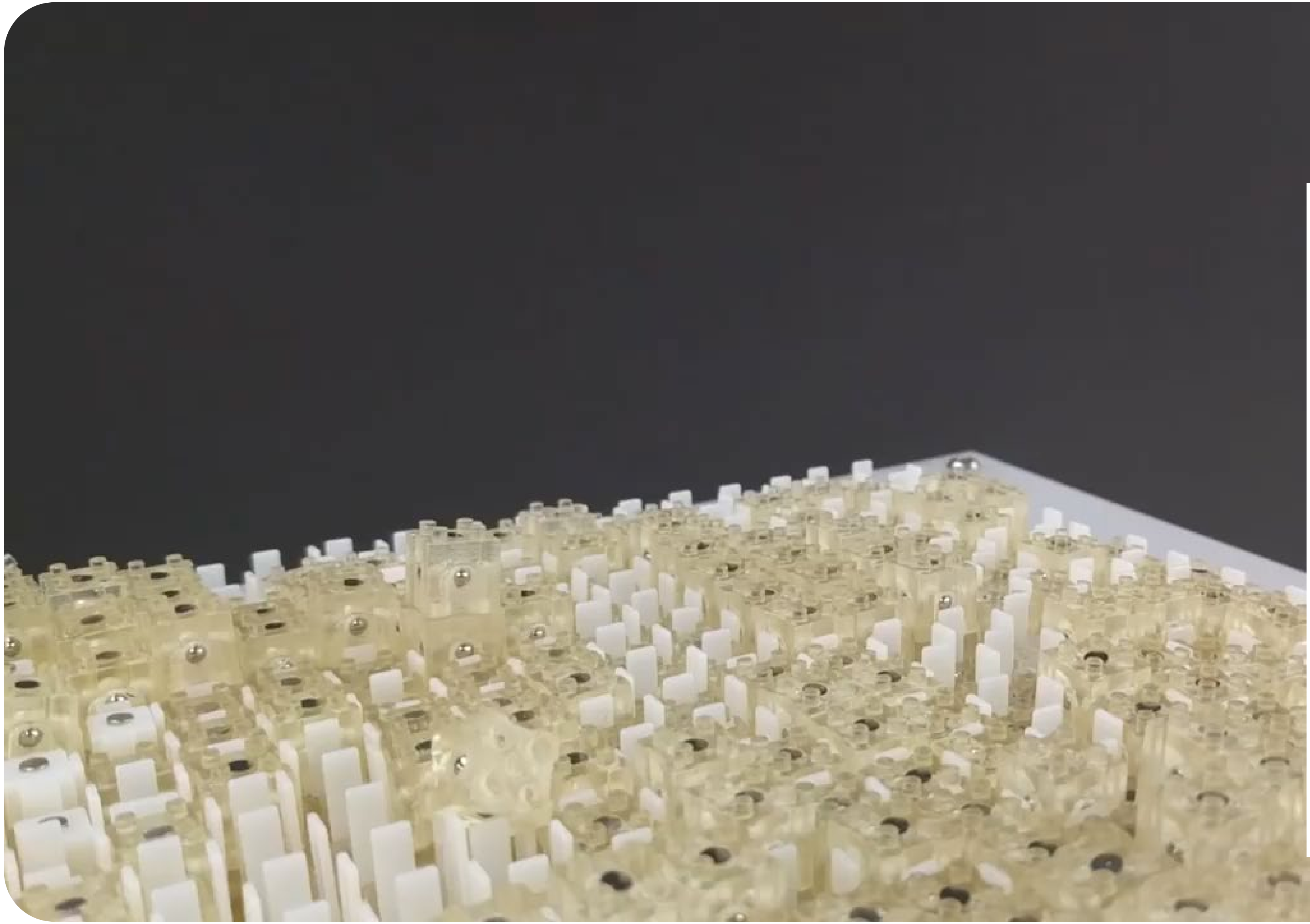
How to further improve the system?

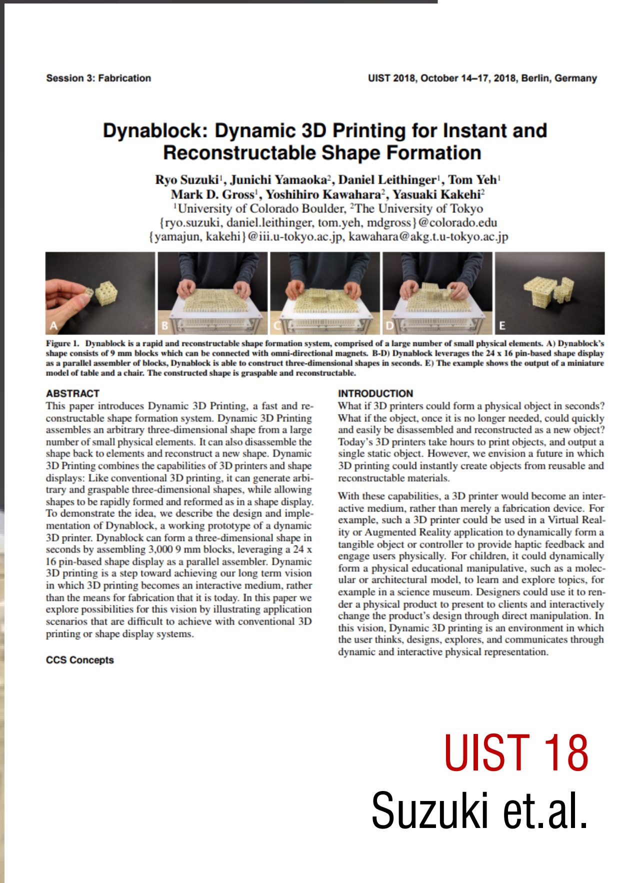
What if we can generate physical models **in seconds**?

What if we can generate physical models **in seconds**?



Fast shape changing speed
But only 2.5D
And it's not detachable





Dynablock: Dynamic 3D Printing for Instant and Reconstructable Shape Formation

Ryo Suzuki[1], Junichi Yamaoka[2], Daniel Leithinger[1], Tom Yeh[1]
Mark D. Gross[1], Yoshihiro Kawahara[2], Yasuaki Kakehi[2]
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Figure 1. Dynablock is a rapid and reconstructable shape formation system, comprised of a large number of small physical elements. A) Dynablock's shape consists of 9 mm blocks which can be connected with omni-directional magnets. B-D) Dynablock leverages the 24 x 16 pin-based shape display as a parallel assembler of blocks, Dynablock is able to construct three-dimensional shapes in seconds. E) The example shows the output of a miniature model of table and a chair. The constructed shape is graspable and reconstructable.

ABSTRACT
This paper introduces Dynamic 3D Printing, a fast and reconstructable shape formation system. Dynamic 3D Printing assembles an arbitrary three-dimensional shape from a large number of small physical elements. It can also disassemble the shape back to elements and reconstruct a new shape. Dynamic 3D Printing combines the capabilities of 3D printers and shape displays: Like conventional 3D printing, it can generate arbitrary and graspable three-dimensional shapes, while allowing shapes to be rapidly formed and reformed as in a shape display. To demonstrate the idea, we describe the design and implementation of Dynablock, a working prototype of a dynamic 3D printer. Dynablock can form a three-dimensional shape in seconds by assembling 3,000 9 mm blocks, leveraging a 24 x 16 pin-based shape display as a parallel assembler. Dynamic 3D printing is a step toward achieving our long term vision in which 3D printing becomes an interactive medium, rather than the means for fabrication that it is today. In this paper we explore possibilities for this vision by illustrating application scenarios that are difficult to achieve with conventional 3D printing or shape display systems.

CCS Concepts

INTRODUCTION
What if 3D printers could form a physical object in seconds? What if the object, once it is no longer needed, could quickly and easily be disassembled and reconstructed as a new object? Today's 3D printers take hours to print objects, and output a single static object. However, we envision a future in which 3D printing could instantly create objects from reusable and reconstructable materials.

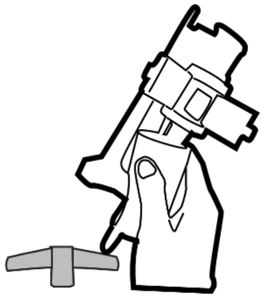
With these capabilities, a 3D printer would become an interactive medium, rather than merely a fabrication device. For example, such a 3D printer could be used in a Virtual Reality or Augmented Reality application to dynamically form a tangible object or controller to provide haptic feedback and engage users physically. For children, it could dynamically form a physical educational manipulative, such as a molecular or architectural model, to learn and explore topics, for example in a science museum. Designers could use it to render a physical product to present to clients and interactively change the product's design through direct manipulation. In this vision, Dynamic 3D printing is an environment in which the user thinks, designs, explores, and communicates through dynamic and interactive physical representation.

UIST 18
Suzuki et.al.

Fabrication + Interactivity

Interactive Fabrication

Lower the design barriers
for 3D modeling



Fabrication for Interaction

Raise the output capabilities
of a fabricated object

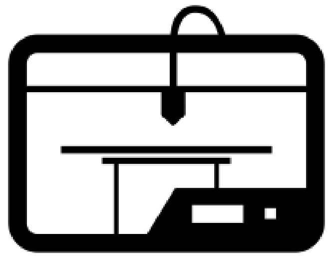
Fabrication + Interactivity

Interactive Fabrication

Lower the design barriers
for 3D modeling

Fabrication for Interaction

Raise the output capabilities
of a fabricated object



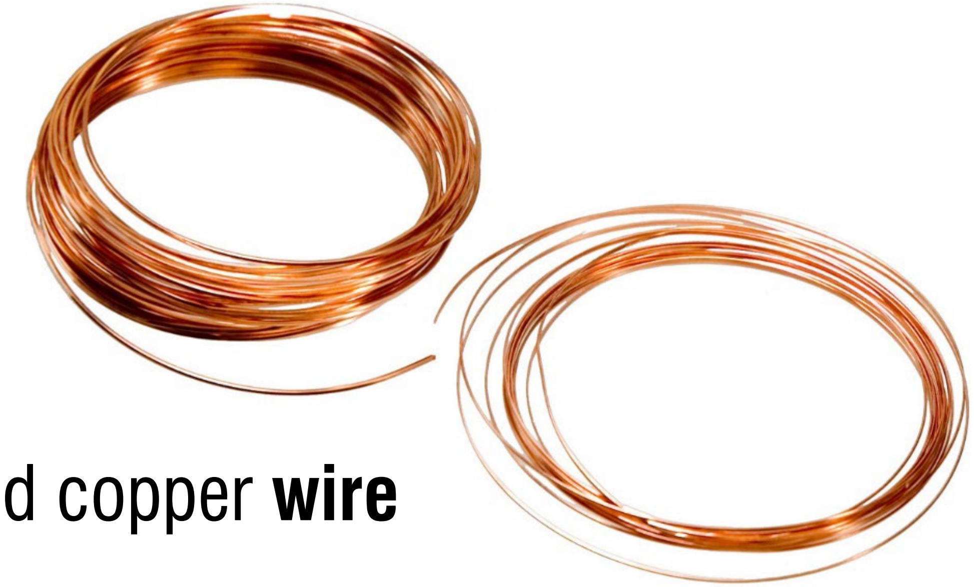
A 3D Printer for Interactive Electromagnetic Devices

Huaishu Peng | François Guimbretière | James McCann | Scott Hudson

Disney Research   Cornell University   Carnegie Mellon

UIST 2016

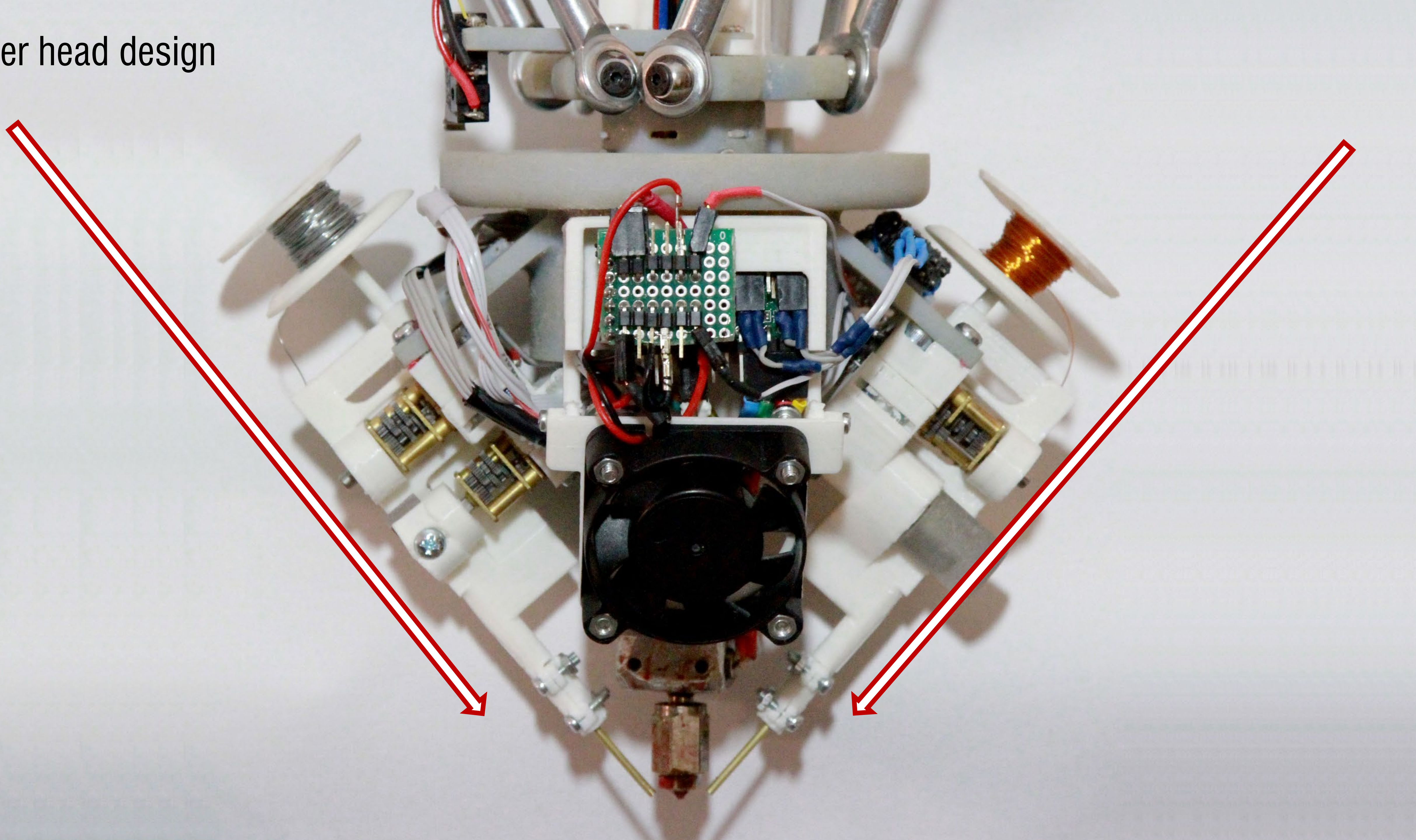
Winding continuous strands of **wire**
inside a 3D printed object across printed layers



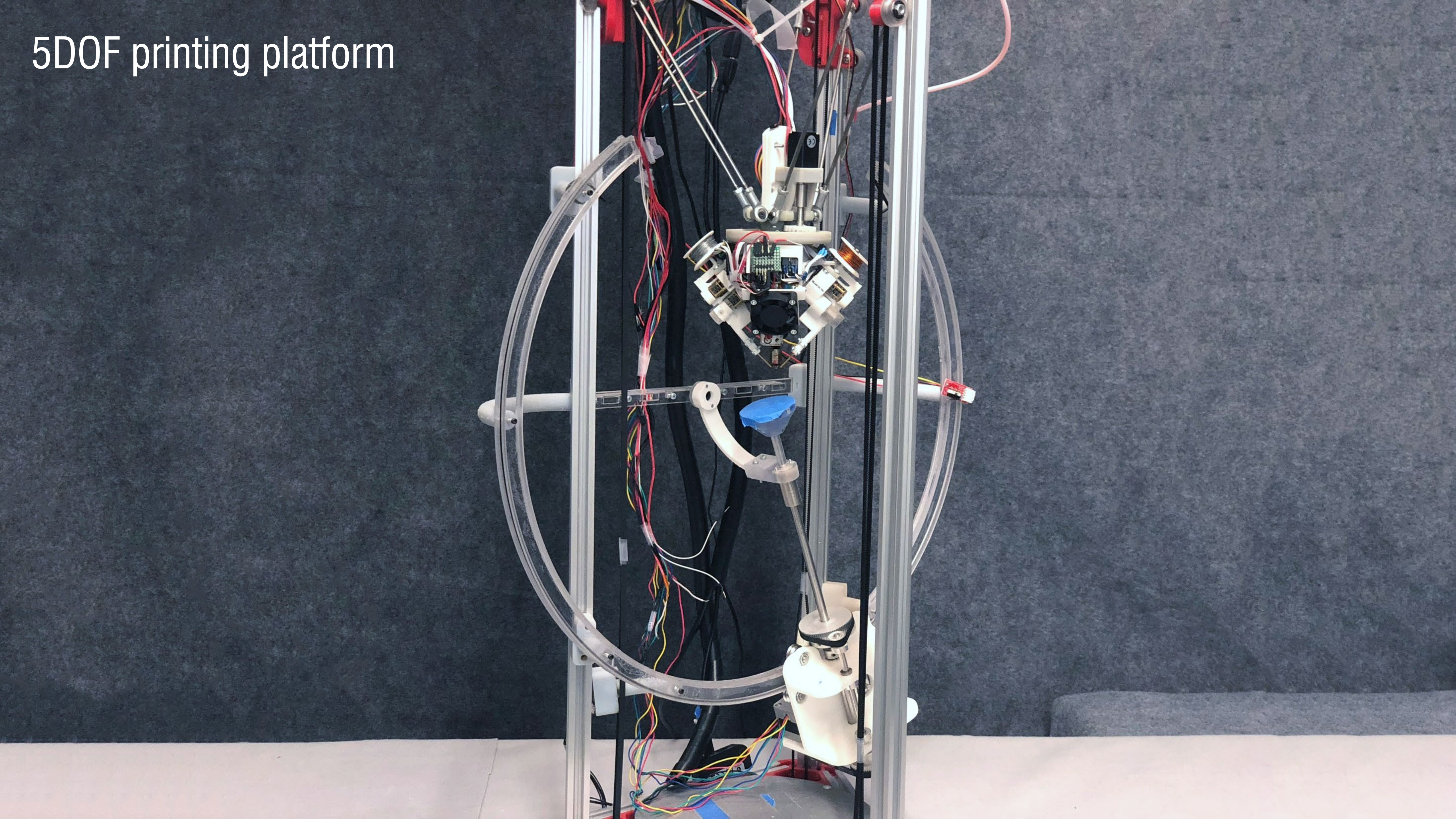
Isolated copper **wire**

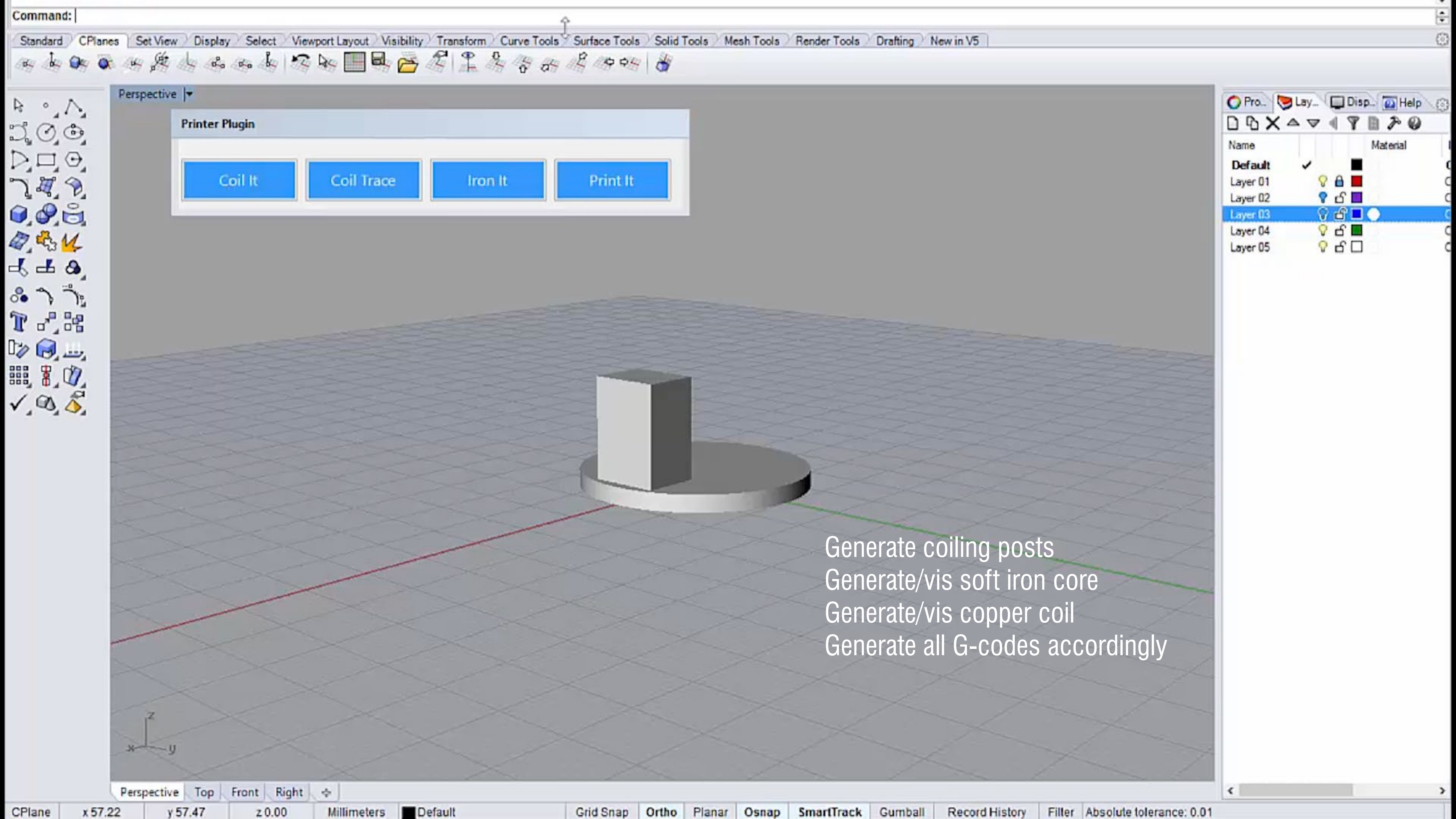
Soft iron **wire**

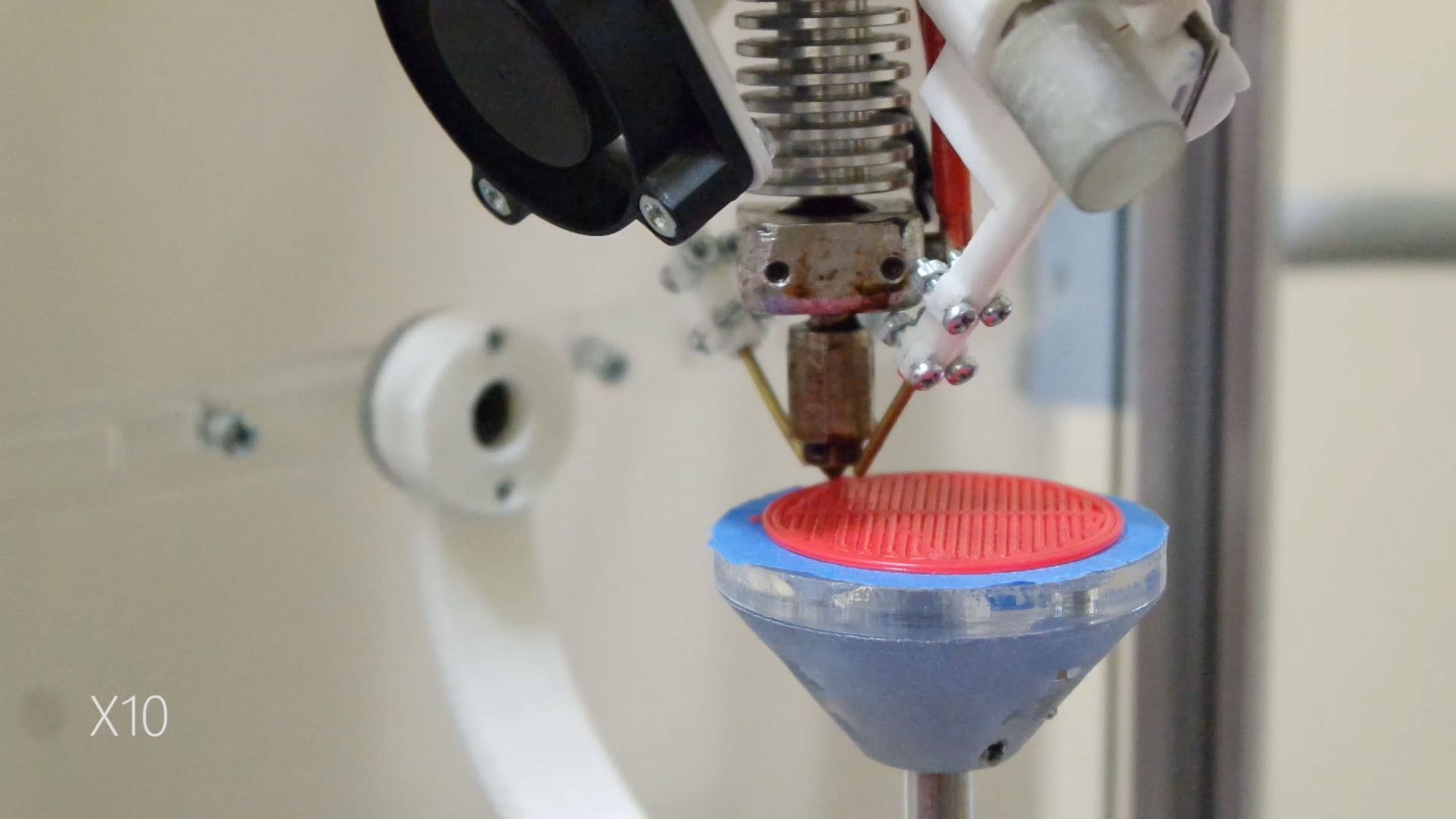
Printer head design

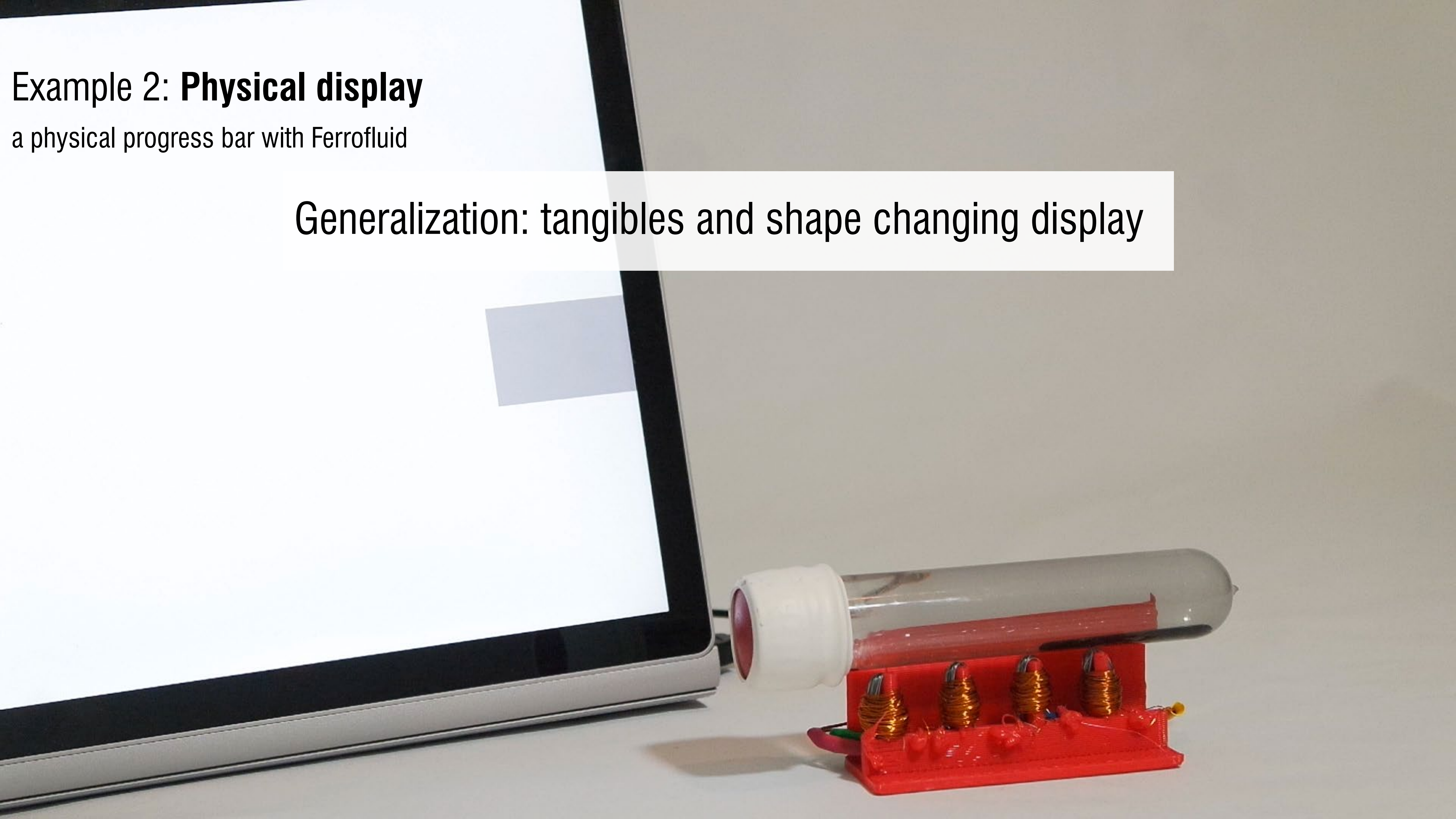


5DOF printing platform

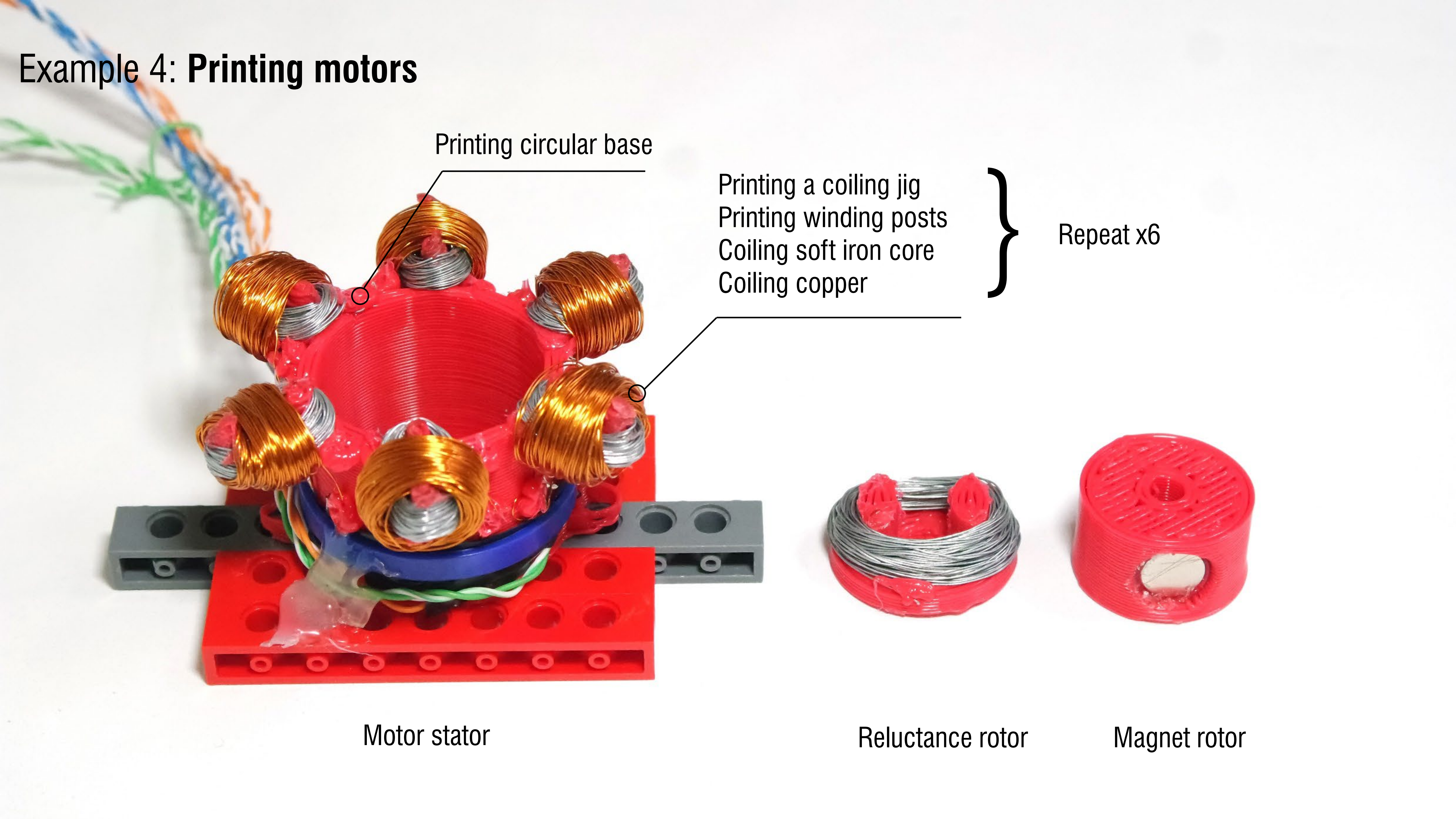



Command:
Standard
CPlanes
Set View
Display
Select
Viewport Layout
Visibility
Transform
Curve Tools
Surface Tools
Solid Tools
Mesh Tools
Render Tools
Drafting
New in V5
Perspective
Printer Plugin
Coil It
Coil Trace
Iron It
Print It
Pro...
Lay...
Disp...
Help
Name
Material
Default
Layer 01
Layer 02
Layer 03
Layer 04
Layer 05
Generate coiling posts
Generate/vis soft iron core
Generate/vis copper coil
Generate all G-codes accordingly
Perspective
Top
Front
Right
CPlane
x 57.22
y 57.47
z 0.00
Millimeters
Default
Grid Snap
Ortho
Planar
Osnap
SmartTrack
Gumball
Record History
Filter
Absolute tolerance: 0.01


X10

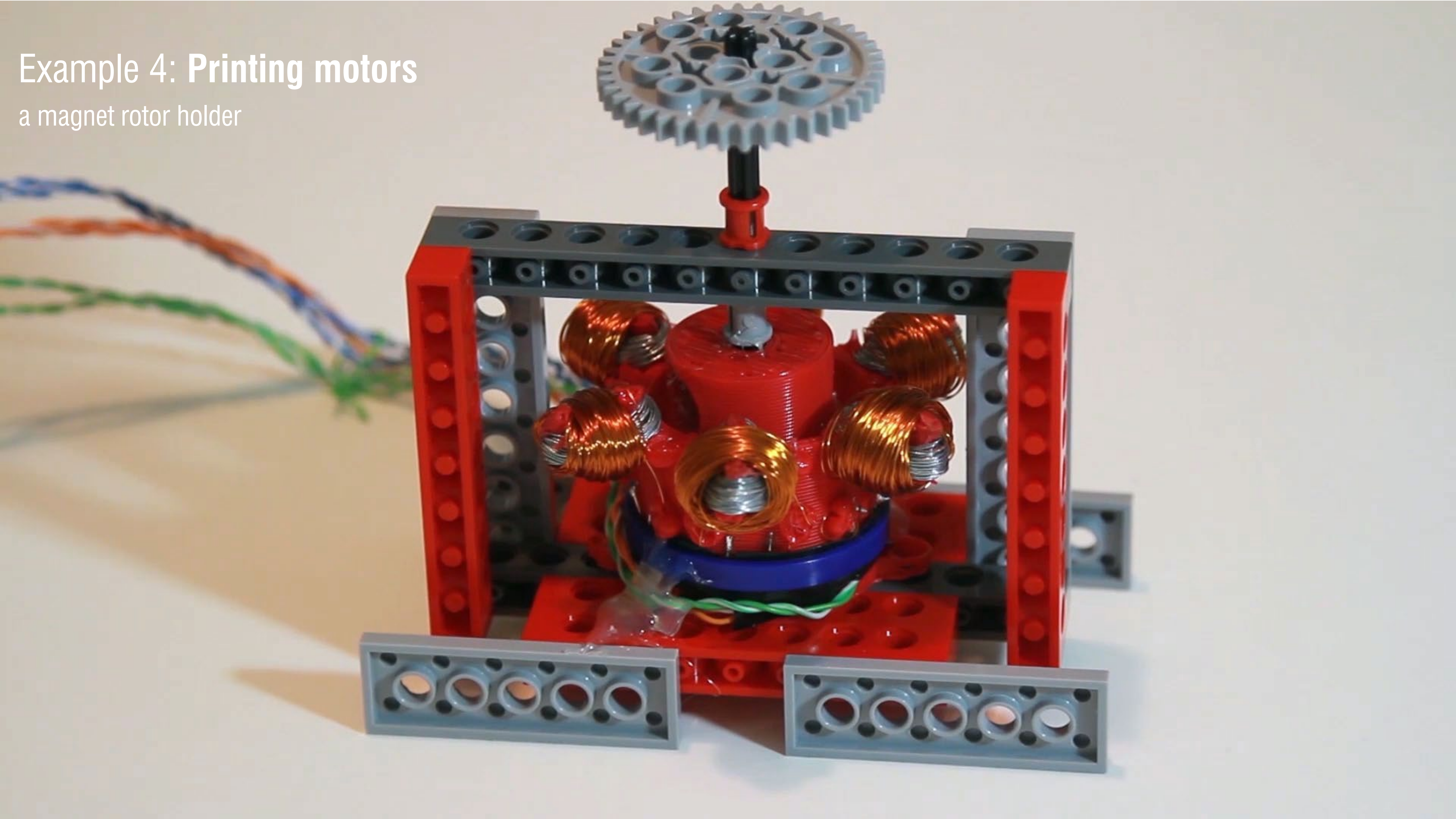

Example 2: **Physical display**
a physical progress bar with Ferrofluid
Generalization: tangibles and shape changing display

Example 4: **Printing motors**



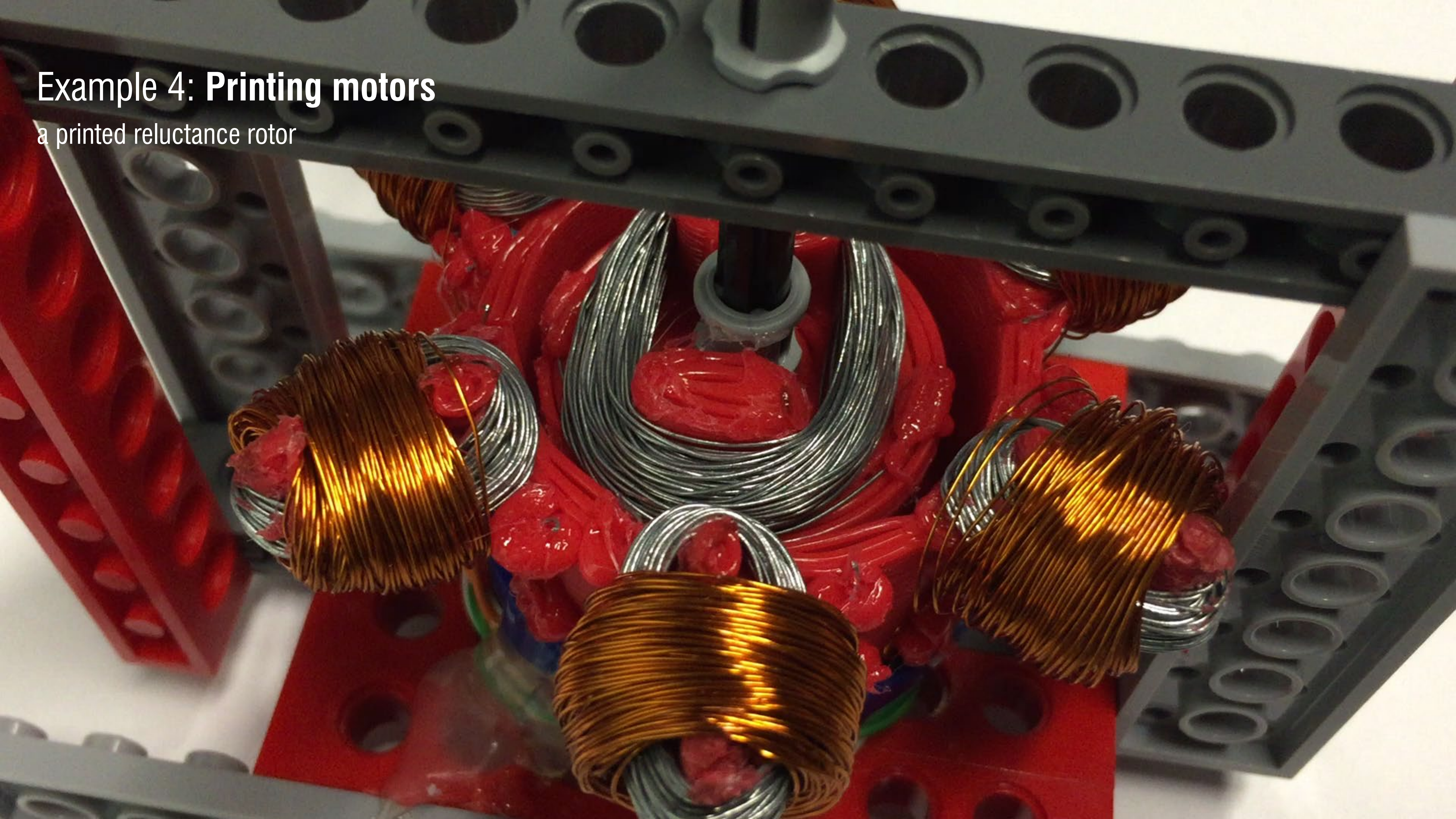
Example 4: **Printing motors**

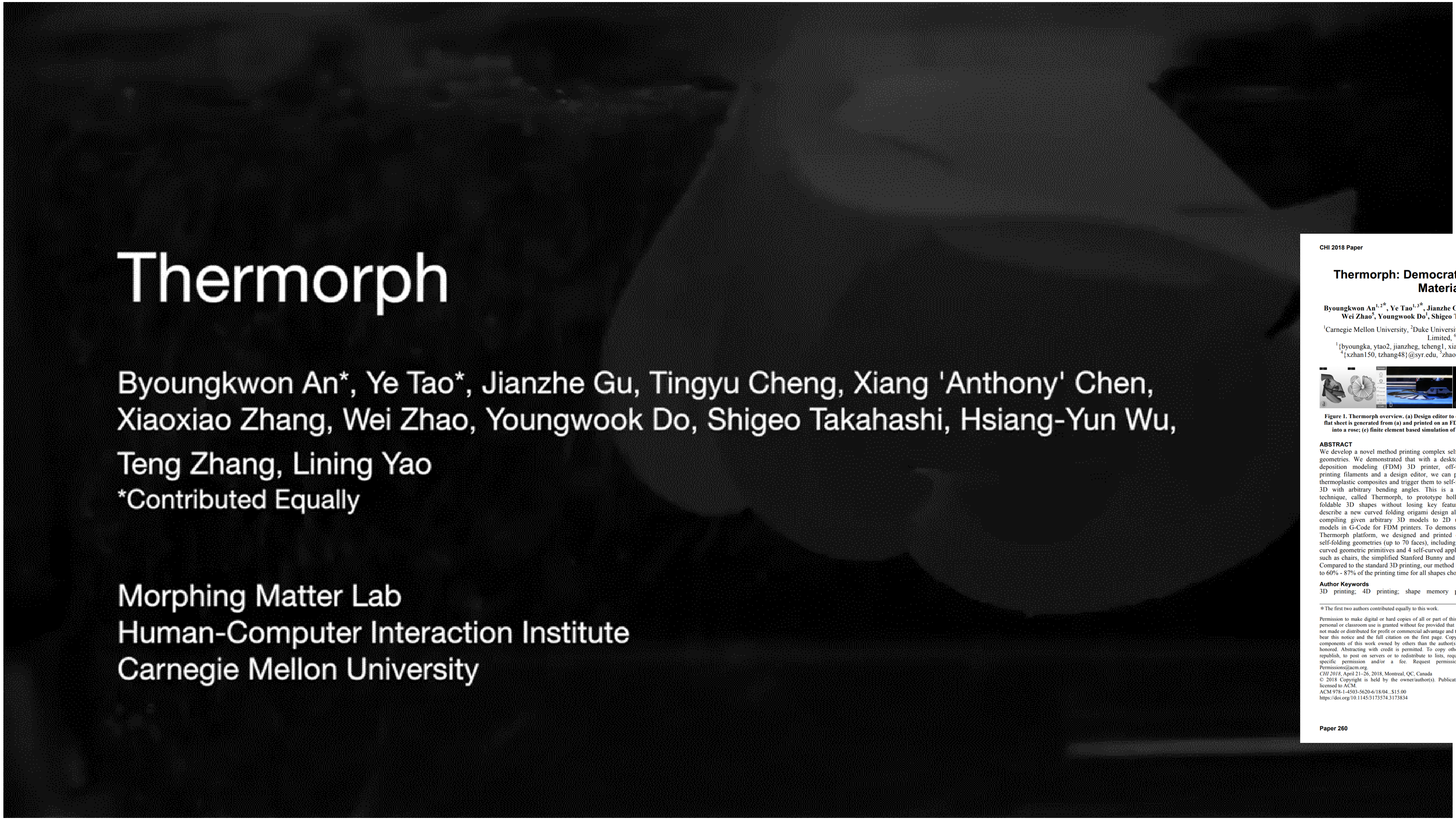
a magnet rotor holder



Example 4: **Printing motors**

a printed reluctance rotor



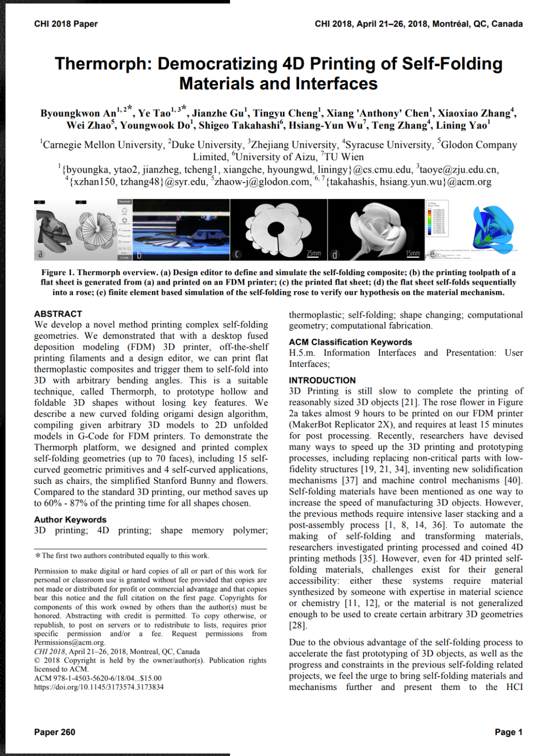


Thermorph

Byoungkwon An*, Ye Tao*, Jianzhe Gu, Tingyu Cheng, Xiang 'Anthony' Chen, Xiaoxiao Zhang, Wei Zhao, Youngwook Do, Shigeo Takahashi, Hsiang-Yun Wu, Teng Zhang, Lining Yao

*Contributed Equally

Morphing Matter Lab
Human-Computer Interaction Institute
Carnegie Mellon University



Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces

Byoungkwon An[1, 2*], Ye Tao[1, 3*], Jianzhe Gu[1], Tingyu Cheng[1], Xiang 'Anthony' Chen[1], Xiaoxiao Zhang[4], Wei Zhao[5], Youngwook Do[1], Shigeo Takahashi[6], Hsiang-Yun Wu[7], Teng Zhang[4], Lining Yao[1]

[1]Carnegie Mellon University, [2]Duke University, [3]Zhejiang University, [4]Syracuse University, [5]Glodon Company Limited, [6]University of Aizu, [7]TU Wien

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Figure 1. Thermorph overview. (a) Design editor to define and simulate the self-folding composite; (b) the printing toolpath of a flat sheet is generated from (a) and printed on an FDM printer; (c) the printed flat sheet; (d) the flat sheet self-folds sequentially into a rose; (e) finite element based simulation of the self-folding rose to verify our hypothesis on the material mechanism.

ABSTRACT
We develop a novel method printing complex self-folding geometries. We demonstrated that with a desktop fused deposition modeling (FDM) 3D printer, off-the-shelf printing filaments and a design editor, we can print flat thermoplastic composites and trigger them to self-fold into 3D with arbitrary bending angles. This is a suitable technique, called Thermorph, to prototype hollow and foldable 3D shapes without losing key features. We describe a new curved folding origami design algorithm, compiling given arbitrary 3D models to 2D unfolded models in G-Code for FDM printers. To demonstrate the Thermorph platform, we designed and printed complex self-folding geometries (up to 70 faces), including 15 self-curved geometric primitives and 4 self-curved applications, such as chairs, the simplified Stanford Bunny and flowers. Compared to the standard 3D printing, our method saves up to 60% - 87% of the printing time for all shapes chosen.

Author Keywords
3D printing; 4D printing; shape memory polymer; thermoplastic; self-folding; shape changing; computational geometry; computational fabrication.

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation: User Interfaces;

INTRODUCTION
3D Printing is still slow to complete the printing of reasonably sized 3D objects [21]. The rose flower in Figure 2a takes almost 9 hours to be printed on our FDM printer (MakerBot Replicator 2X), and requires at least 15 minutes for post processing. Recently, researchers have devised many ways to speed up the 3D printing and prototyping processes, including replacing non-critical parts with low-fidelity structures [19, 21, 34], inventing new solidification mechanisms [37] and machine control mechanisms [40]. Self-folding materials have been mentioned as one way to increase the speed of manufacturing 3D objects. However, the previous methods require intensive laser stacking and a post-assembly process [1, 8, 14, 36]. To automate the making of self-folding and transforming materials, researchers investigated printing processed and coined 4D printing methods [35]. However, even for 4D printed self-folding materials, challenges exist for their general accessibility: either these systems require material synthesized by someone with expertise in material science or chemistry [11, 12], or the material is not generalized enough to be used to create certain arbitrary 3D geometries [28].

Due to the obvious advantage of the self-folding process to accelerate the fast prototyping of 3D objects, as well as the progress and constraints in the previous self-folding related projects, we feel the urge to bring self-folding materials and mechanisms further and present them to the HCI

* The first two authors contributed equally to this work.

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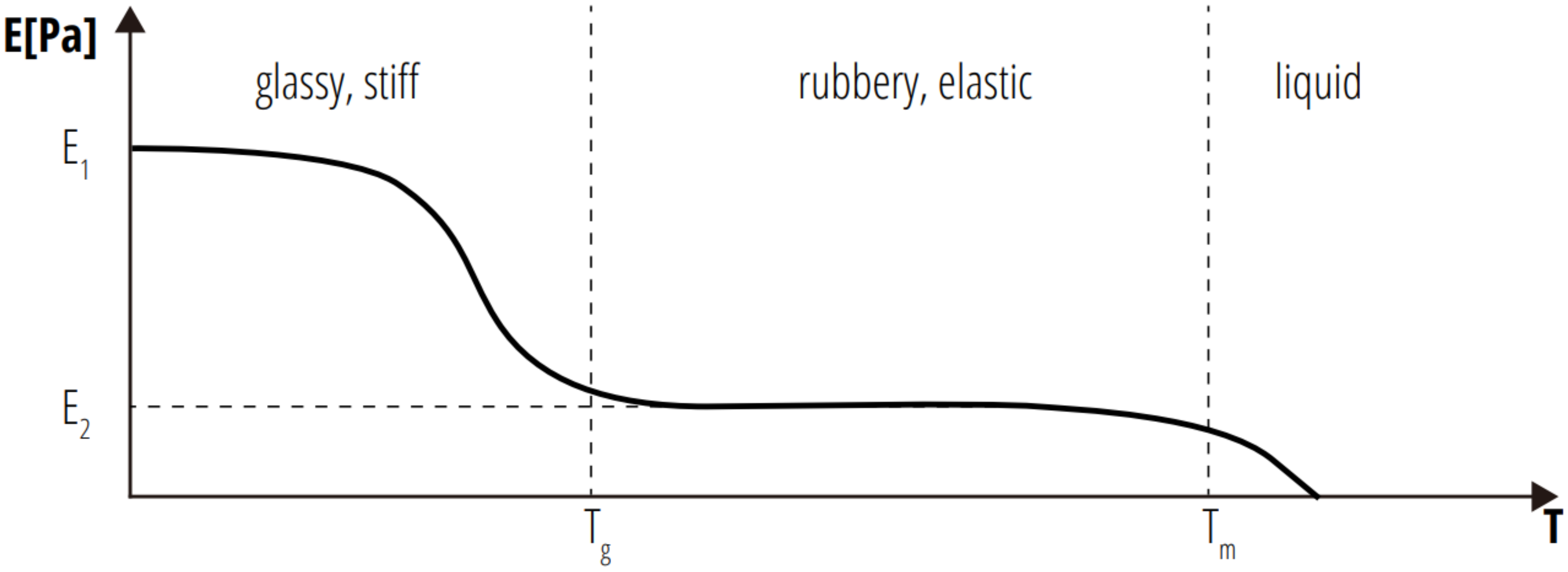
https://doi.org/10.1145/3173574.3173834

CHI 18
An et.al.

Shape memory of thermoplastic

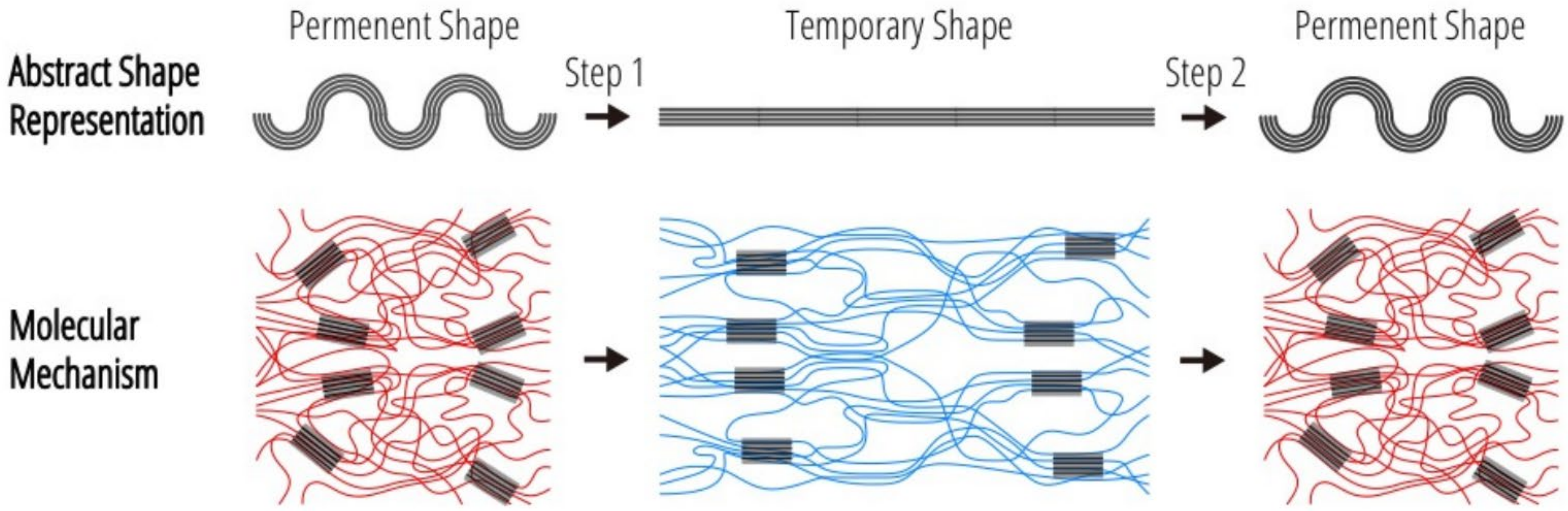
Shape memory thermoplastic has the capability of changing its shape upon temperature changes



glass transition temperature

melting temperature

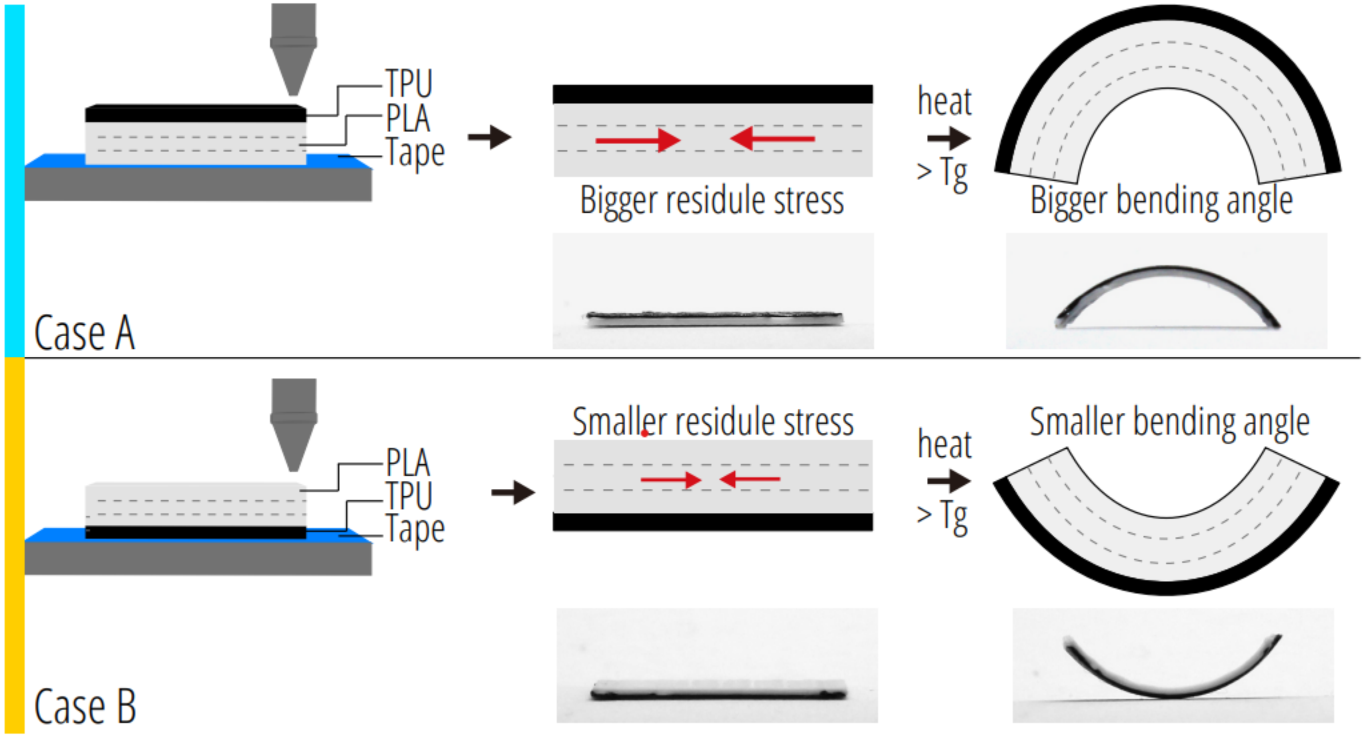
Shape memory of thermoplastic



During the printing process, the polymer chain is being rearranged and residual stress can be built: when PLA is being extruded, the polymer chain is pulled and straight; it will be forced to keep the straight state after it quickly cools and solidifies.

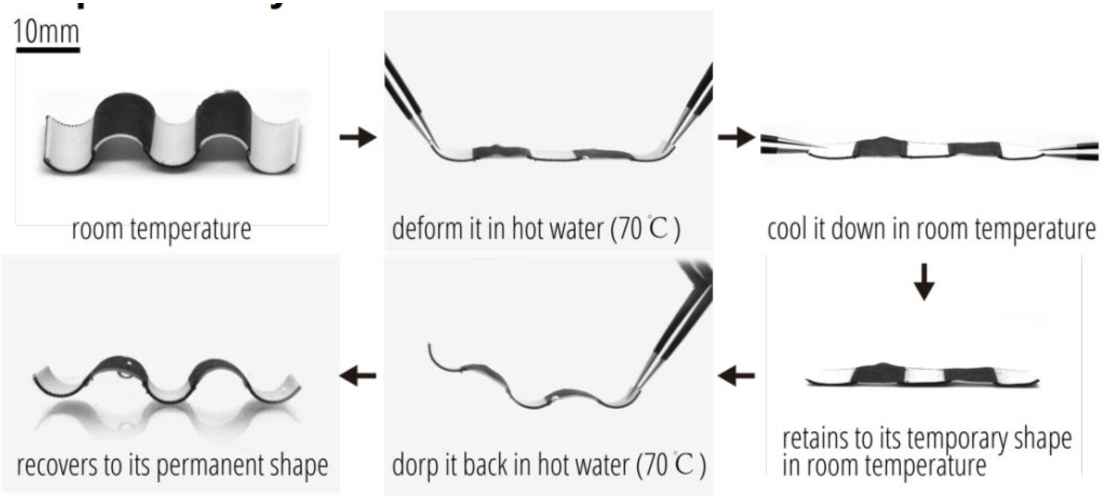
If we reheat the solidified PLA, it will release the residual stress, shorten along the printing direction

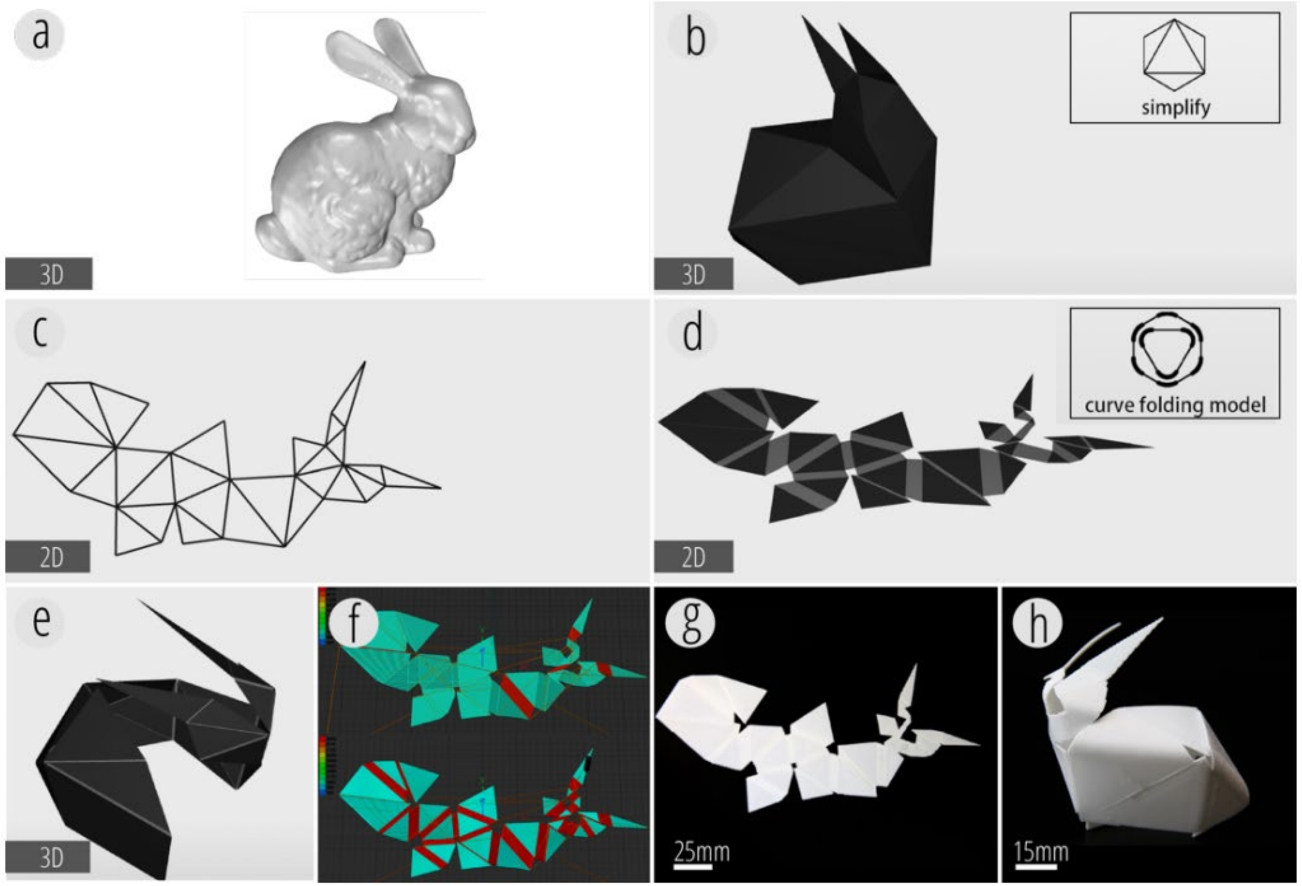
Shape memory of thermoplastic



a bi-layer structure: one layer of Thermopolyurethane (TPU) as the constrain layer and three layers of PLA as the active layer. Together these four layers form an actuator.

Shape memory of thermoplastic





Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking

Wen Wang[1,2*], Lining Yao[1*], Teng Zhang[3], Chin-Yi Cheng[1], Daniel Levine[1], Hiroshi Ishii[1]

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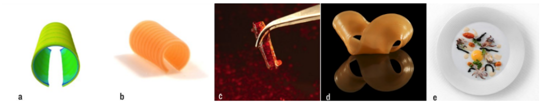

Figure 1. (a-b) Bending simulation of edible film and its corresponding actual sample; (c) self-wrapping water sushi; (d) 3D food from flat 2D film; (e) dish design with squid ink flavored twisting noodle.

ABSTRACT
We developed a concept of transformative appetite, where edible 2D films made of common food materials (protein, cellulose or starch) can transform into 3D food during cooking. This transformation process is triggered by water adsorption, and it is strongly compatible with the 'flat packaging' concept for substantially reducing shipping costs and storage space. To develop these transformable foods, we performed material-based design, established a hybrid fabrication strategy, and conducted performance simulation. Users can customize food shape transformations through a pre-defined simulation platform, and then fabricate these designed patterns using additive manufacturing. Three application techniques are provided - 2D-to-3D folding, hydration-induced wrapping, and temperature-induced self-fragmentation, to present the shape, texture, and interaction with food materials. Based on this concept, several dishes were created in the kitchen, to demonstrate the futuristic dining experience through materials-based interaction design.

∗The first two authors contributed equally to this work.

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Author Keywords
Transformable food; water interaction; 2D-to-3D; autonomous shape-changing; anisotropic swelling; interactive edibles; dish design

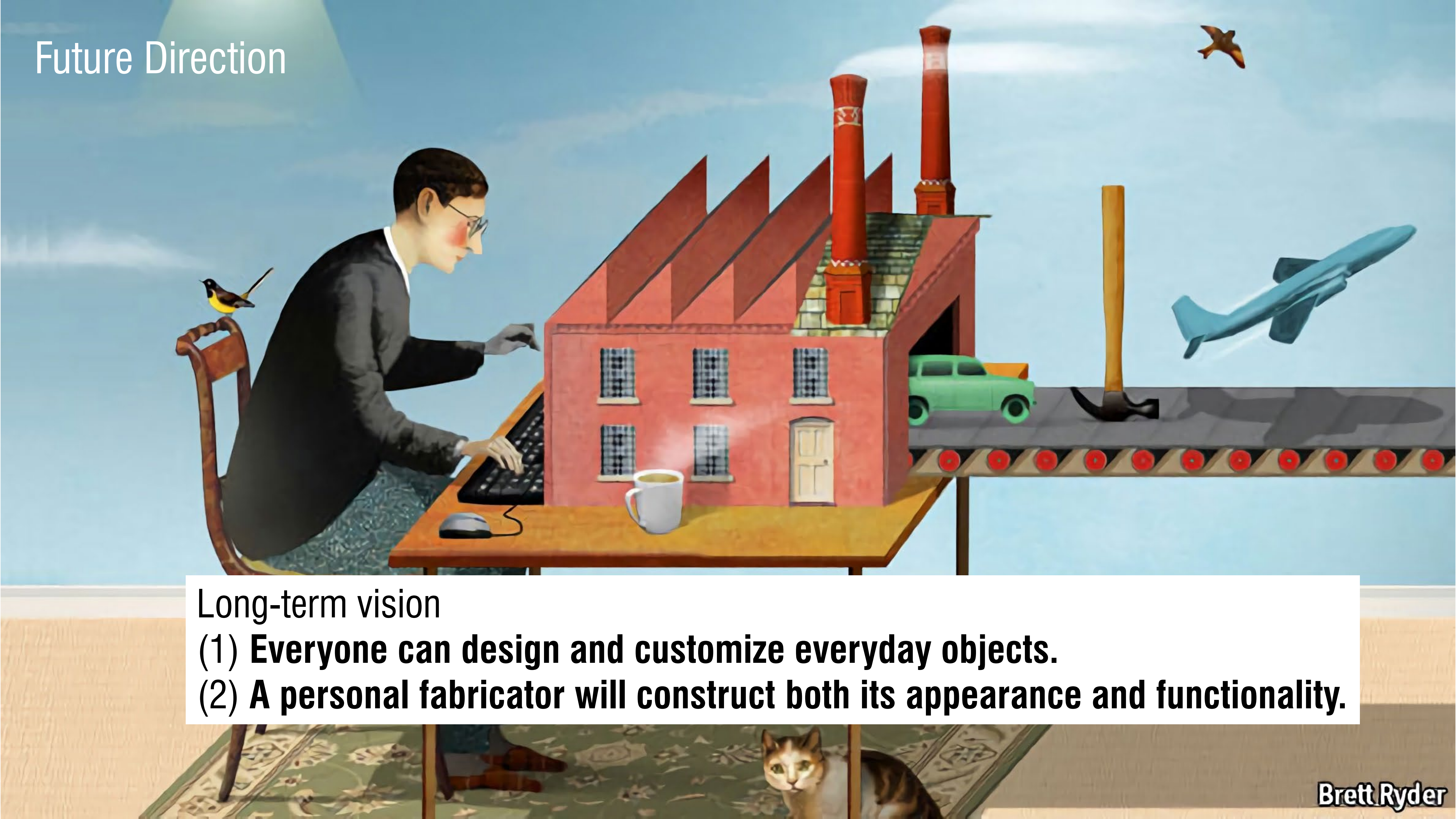
ACM Classification Keywords
Design

INTRODUCTION
The concept of 'flat packaging' was coined by IKEA, a Swedish furniture company, which manufactures 2D furniture segments for assembly into 3D furniture by people in their own homes. This concept enables the company to benefit from low shipping costs due to compactness of the 2D segments while maintaining the desired function and appearance of the 3D end products.

Here we propose a similar concept for the food industry, where edible materials are manufactured into highly compact 2D segments and transformed in the kitchen or on the dining table into 3D structures, which bring different textures and eating experiences to diners. We combine material science, computer-aided design and additive manufacturing to enable autonomous transformations in pre-defined ways, which liberates users from tedious cooking tasks. Specifically, through three techniques and dish examples, we aim to demonstrate that the 2D-to-3D transformation via hydration process is good for 1) creating unique mouth feel textures and shapes to enrich the eating experiences; 2) achieving programmable food transformations; and 3) save space during shipping and storage.

CHI 17
Wang et.al.

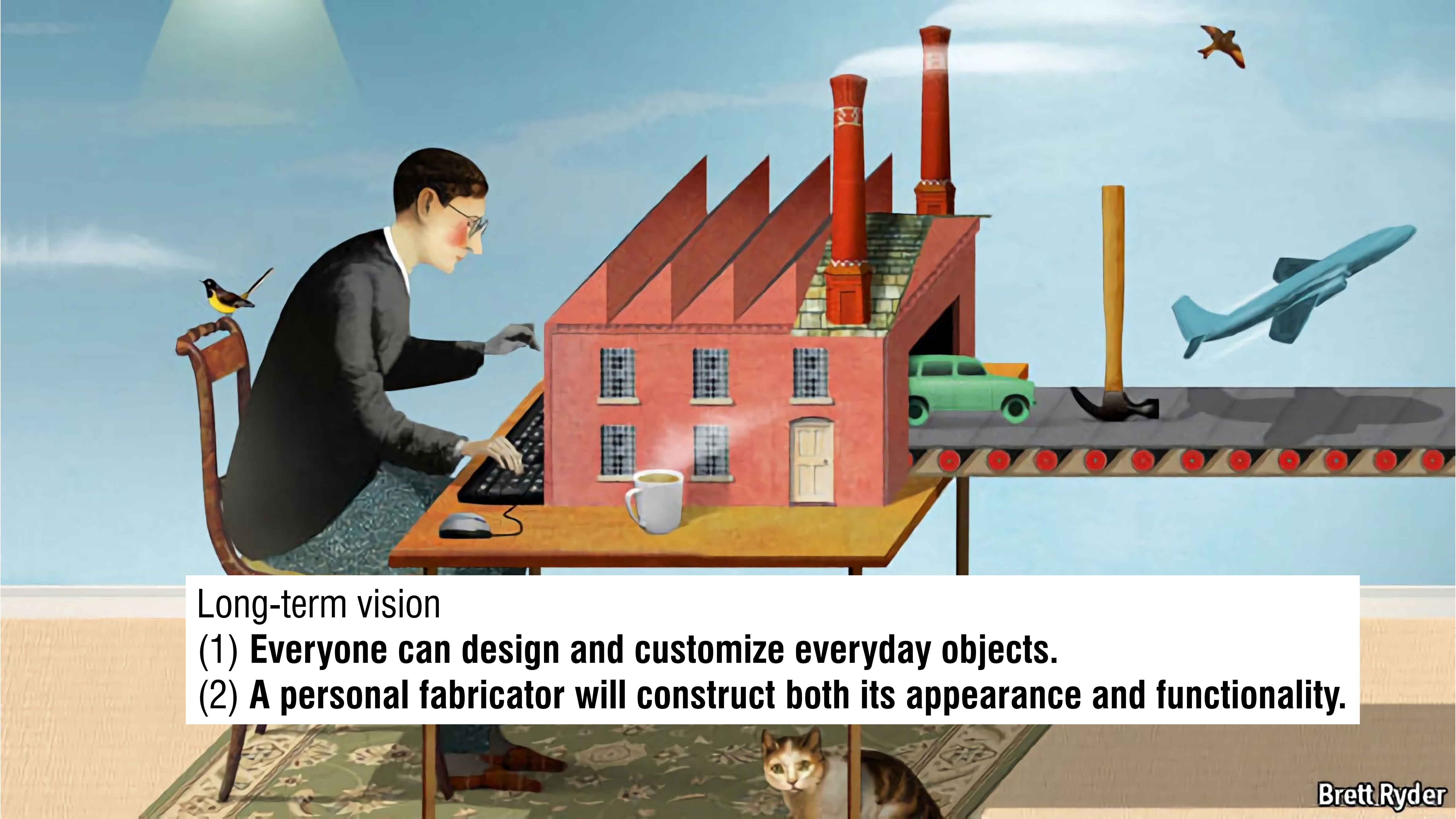
Future Direction



Long-term vision

(1) **Everyone can design and customize everyday objects.**

(2) **A personal fabricator will construct both its appearance and functionality.**



Long-term vision

(1) **Everyone can design and customize everyday objects.**

(2) **A personal fabricator will construct both its appearance and functionality.**

Optional readings

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 repeat 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.

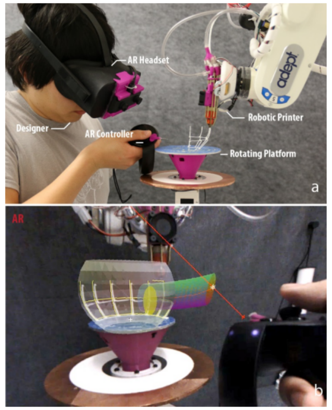

Figure 1: a) RoMA overview. b). Designer view from the AR headset. The designer creates a digital spout while the robot prints the teapot body. Digital model is overlaid onto the physical model.

*The two authors contributed equally to this work.

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Peng et.al.

KnitUI: Fabricating Interactive and Sensing Textiles with Machine Knitting

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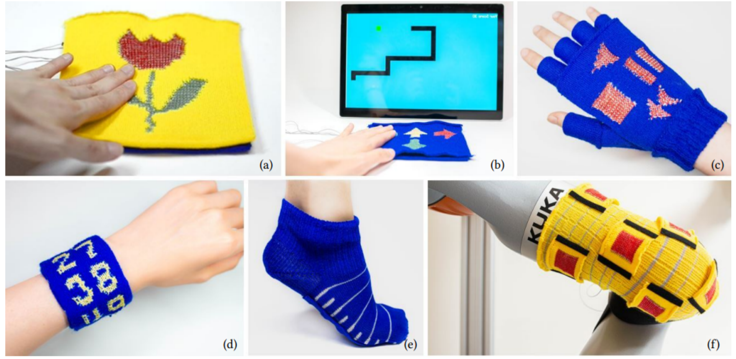

Figure 1: *Example applications of KnitUI:* *(a) interactive educational toys, (b) game controller, (c) music controller glove, (d) numpad wrist wrap, (e) tactile sensing socks, and (f) tactile robotic skin.*

ABSTRACT
With the recent interest in wearable electronics and smart garments, digital fabrication of sensing and interactive textiles is in increasing demand. Recently, advances in digital machine knitting offer opportunities for the programmable, rapid fabrication of soft, breathable textiles. In this paper, we present *KnitUI*, a novel, accessible machine-knitted user interface based on resistive pressure sensing. Employing conductive yarns and various machine knitting techniques, we computationally design and automatically fabricate the double-layered resistive sensing structures as well as the coupled conductive connection traces with minimal manual post-processing. We present an interactive design interface for users to customize KnitUI's colors, sizes, positions, and shapes. After investigating design parameters for the optimized sensing and interactive performance, we demonstrate KnitUI as a portable, deformable, washable, and customizable interactive and sensing platform. It obtains diverse applications, including wearable user interfaces, tactile sensing wearables, and artificial robot skin.

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