Exploring 3D Printed Interaction

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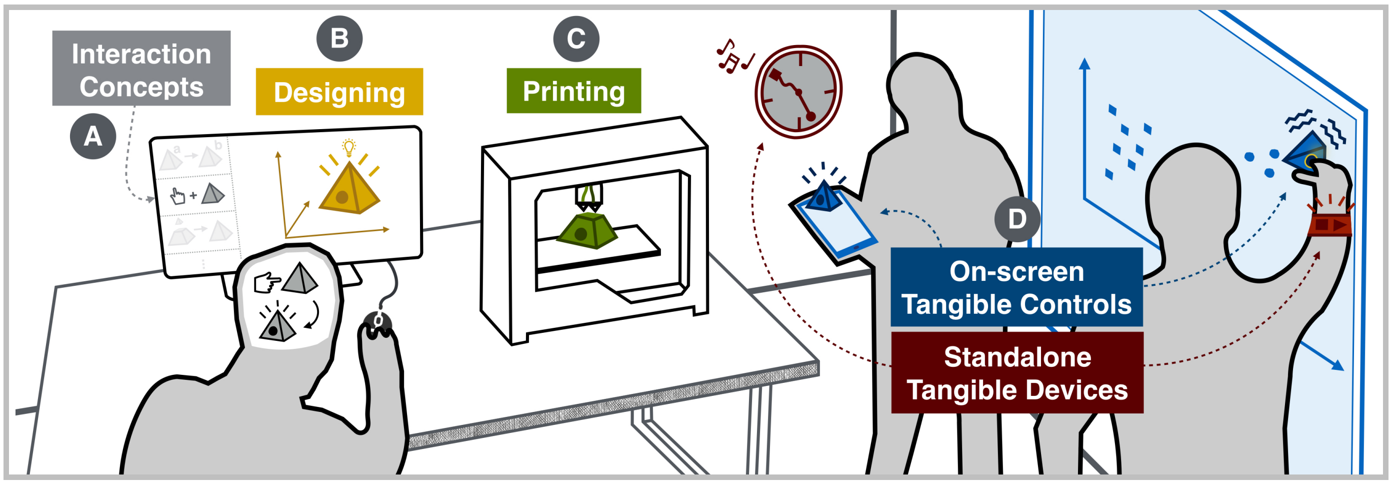

Figure 1: A vision of 3D fabrication environments: Guided by tangible interaction concepts (A), users turn ideas into a 3D model (B), that is 3D printed (C) and used as a standalone tangible device or an on-screen tangible control on interactive surfaces (D).

ABSTRACT
3D printing is widely used to physically prototype the look and feel of 3D objects. However, interaction possibilities of these prototypes are often limited to mechanical parts or post-assembled electronics. Moreover, fabricating interactive 3D printed objects is still an expert task. In my dissertation, I therefore explore how to support users in the design of interactive 3D objects and how to automate the generation of adequate sensing structures. Further, I investigate tangible interaction concepts for 3D printed objects. In this paper, I outline my past and future research towards the fabrication of 3D objects in terms of (1) user-friendly design, (2) automation of fabrication, and (3) tangible interaction concepts for the input modalities touch and deformation.

Author Keywords
3D printing; digital fabrication; rapid prototyping; printed electronics; input sensing; touch; deformation

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INTRODUCTION
As 3D printing is becoming an affordable and versatile technology, non-expert users are enabled to produce highly customized tangible objects. Typically, objects are designed in a 3D modeling tool and are turned into tangible 3D objects by depositing materials. While these closely resemble the form and shape of objects or devices, their interaction possibilities are in many cases limited to only mechanical functions. As a consequence, these objects are in a sense passive [16].

One common approach to overcome this limitation is to *post-assemble* electronic components by attaching them to the 3D object after printing [16, 5]. While practical and widely used, the pre-designed form factors of such components (e.g. limited available sizes or fixed planar shapes) severely constrain their usage on custom-designed 3D objects, making it even more challenging to realize complex interactive 3D objects. Moreover, sensors need to be attached and wired manually, which is often a tedious and error-prone task.

To provide more design flexibility, an emerging stream of research investigates how to integrate customized interactive elements directly within the digital fabrication process [21, 17, 2]. This motivates the underlying idea of my work. I envision the digital fabrication of interactive 3D objects as follows: Like today's desktop 2D printers, 3D printers will be fast, cheap, reliable, and widely available in almost every home or in form of professional 3D copy shops. Interactive objects can be fabricated on-demand in many different shapes, colors, and materials without the need for lavish post-processing. A potential future fabrication environment is illustrated in Figure 1: Based on tangible interaction concepts (A) users digitize their individual ideas into a 3D model by adding various interactive components (B). They can then repeatedly print 3D objects (C) and use them either as *standalone tangible devices* (red) or as *on-screen tangible controls* (blue) on an interactive surface (e.g., a tablet or a wall-sized display) (D). This fabrication environment should be as easy and automatic as today's creation of paper documents with word-processing software and a 2D desktop printer.

My dissertation contributes towards this vision by investigating how users can easily fabricate and use 3D printed tangible objects. More precisely, I focus on three main objectives: (1) I explore how to support users in designing various interactive components onto the digital model of 3D objects (e.g., making parts of an object touch-sensitive, pushable, or blinking). (2) I develop algorithms and techniques to automatically generate and adapt interactive components to the digital model of 3D objects. (3) I study and evaluate the proposed fabrication environment and investigate tangible interaction concepts for various classes of 3D printed objects through user studies.

In the next sections, I review related work and introduce my research objectives. Then, I outline my progress in achieving these objectives and provide an overview of future research.

RELATED WORK

There are various ways to make physical objects interactive that differ based on the degree of automation, i.e. how much manual work is required, and the complexity of the object's geometry (see Figure 2). Objects can be made interactive (1) by external augmentation using camera-projector units, (2) by post-assembling standard electronic components, or (3) by directly fabricating interactive components into the object.

External Augmentation

One common approach to add interactive capabilities to 3D objects is through *external augmentation*, i.e. by tracking and augmenting objects via external sensing devices (e.g., often via depth cameras or projectors). Researcher propose techniques to detect touch through depth sensing [22] or project visual content onto tracked objects [9, 20]. While practical for evaluations, external augmentation requires complex and often stationary setups and is subject to occlusion effects, that restrain the interactive capabilities on the backside.

Post Assembly

Another approach is to embed or attach electrical components to non-interactive objects through *post-assembly*. However, standard components often restrict the design of 3D objects due to their pre-defined form factor. To mitigate this drawback, researchers utilize inkjet printers [8, 11, 4] or vinyl cutters [18] to realize custom-shaped sensors that can be embedded into or wrapped around objects. Another stream of research attaches capacitive [15] or acoustic [12] sensors, or embeds cameras [16] or accelerometers [5]. However, these approaches often involve manual assembly steps, are limited to basic interactions (e.g., discerning simple touch gestures) or are only applicable on geometries with low complexity.

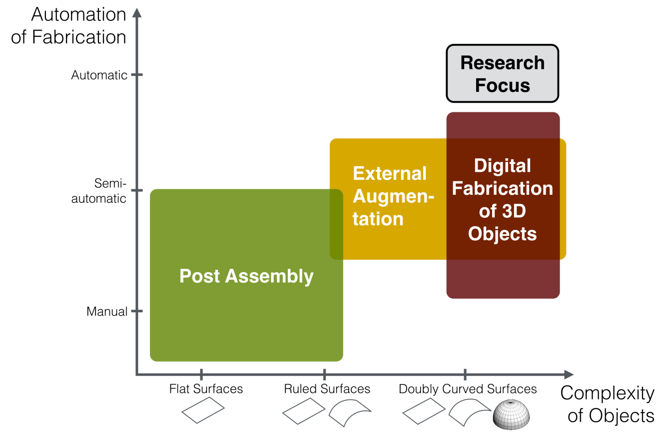

Figure 2: Classification of related work based on the complexity of objects and the automation of fabrication.

Digital Fabrication of 3D Objects

A recent stream of research investigates how to directly integrate interactive capabilities into 3D objects through *digital fabrication*. This includes redirecting in- or output channels through light pipes [21, 2] or unfilled pipes [17] in printed objects. In addition, researchers propose different techniques that integrate conductive parts directly into 3D printed objects by means of conductive wires [3], silicone [13], sprays [14, 7], inks [1], or threads [6]. Lopes et al. suggest a hybrid approach that combines 3D printing with electronic components [10]. However, interactive objects fabricated with these approaches often require specialized printers, additional assembly steps or need to be manually designed by experts.

In contrast to prior work, my research will allow users to automatically fabricate 3D printed tangible objects without the need for complicated 3D design or manual assembly.

RESEARCH OBJECTIVES

My dissertation addresses the research question of how 3D printing can be used to allow users to easily and automatically fabricate tangible interactive objects. In particular, I am working towards the following three inter-connected research objectives (see Figure 3):

1. **Support user-friendly design of interactivity.**
   Once 3D-form and interactivity can be fabricated in a single integrated process, how can users design interactivity in an easy-to-use design environment? How can interactive components be effectively applied to 3D objects?

2. **Automate the generation of interactivity.**
   Which problems of the 3D fabrication pipeline can be automated and how? What are novel sensing structures that also apply on doubly curved objects and do not require manual assembly steps? How can these automatically be applied to doubly curved objects?

3. **Investigate tangible interaction concepts for 3D objects.**
   Novel interactive technologies are often characterized by specific interaction affordances that prevail certain interaction concepts (e.g., touch devices prevail pressing, swiping,

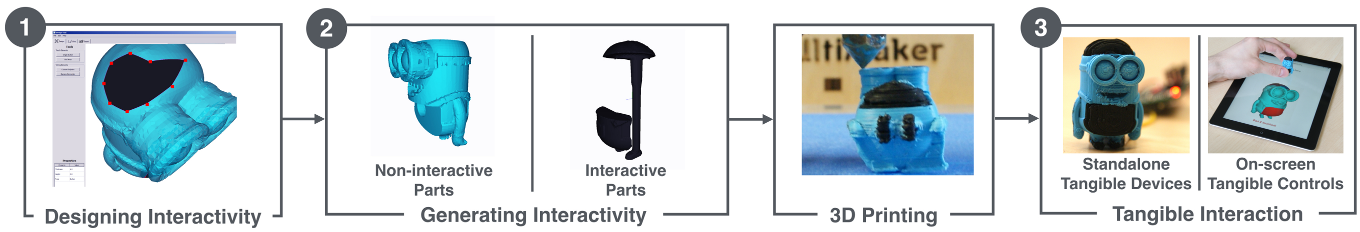

Figure 3: A fabrication pipeline for 3D printed interactive tangible objects.

or pinching). Hence, I want to investigate which tangible interaction concepts are most appropriate for 3D printed objects in the context of on-screen tangible controls and standalone tangible devices. Also, I want to study and evaluate the properties of the proposed fabrication environment (see Figure 1).

CAPRICATE: 3D PRINTED CAPACITIVE TOUCH

In [19], we propose *Capricate*, a fabrication pipeline that enables users to easily design and 3D print customized 3D objects with embedded capacitive multi-touch sensing (see Figure 3). It is based on multi-material 3D printing and is usable with affordable off-the-shelf materials and 3D printers.

Designing Interactivity We address one major issue of the current fabrication approach (with respect to the first research objective): While the emergence of digital fabrication technologies allows users to rapidly *print* custom 3D objects, the *design* of touch electrodes is still a tedious task and often requires expert knowledge in computer-aided design. This is partially due to the fact that custom-shaped areas on a 3D surface need to be selected, extruded, and fused manually with the original model. Also, when designing complex touch grids, many touch electrodes need to be designed and wired by hand and possibly have to be mapped onto a doubly curved surface (see Figure 2). Adding capacitive touch to such complex surfaces is one of the main contributions of Capricate.

To further ease the design, we propose a simple design tool that allows users to create custom-shaped touch sensors on many 3D objects via a two-step interaction technique:
(1) Supported by a 3D visualization, the user indicates a rough position and size of either a touch button or grid on the 3D surface. By clicking, the sensor is applied to the desired location.
(2) Then, the user can fine-grain the shape of the initial selection by dragging edge points or by adding new edge points between two lines (see the black selection with red edge points in Figure 3.1).

Generating Interactivity After the user has finished the design, the tool automatically adds wires to the object and provides fabrication files that can be used to directly print the object with a standard off-the-shelf 3D printer. We further contribute two capacitive touch sensing techniques that operate on doubly curved surfaces. This eases the tedious generation of touch grids consisting of a multitude of touch electrodes that otherwise would need to be created and wired manually.

Tangible Interaction As illustrated in Figure 1, 3D printed objects can be used either as standalone tangible devices or on-screen tangible controls. We further propose three promising application scenarios: (1) Rapid prototyping of physical input devices, (2) wearable computing devices, and (3) printed tangible user interfaces. Figure 4 (top row) shows an on-screen directional pad (on a smart phone) and a touch-sensitive standalone bracelet fabricated with Capricate.

FUTURE RESEARCH

I plan to extend the aforesaid research objectives as follows.

Towards objective 1. In the next step, I will extend the touch-centric design tool presented in [19] to a more general framework that allows users to design and model various other interactive components and modalities (e.g., deformation or pressure) on the 3D model of an object. In a study with makers, I will then evaluate my approach (e.g., efficiency or powerfulness of fabrication) compared to post assembling interactive components to ordinary 3D printed objects.

Towards objective 2. Many common sensing structures (e.g., touch grids) are rarely applicable to arbitrarily shaped 3D objects that are producible with 3D printers. Hence, I plan to investigate other input modalities that most probably require novel 3D sensing structures. As a first step, I plan to explore *deformation*, i.e. altering a 3D geometry without

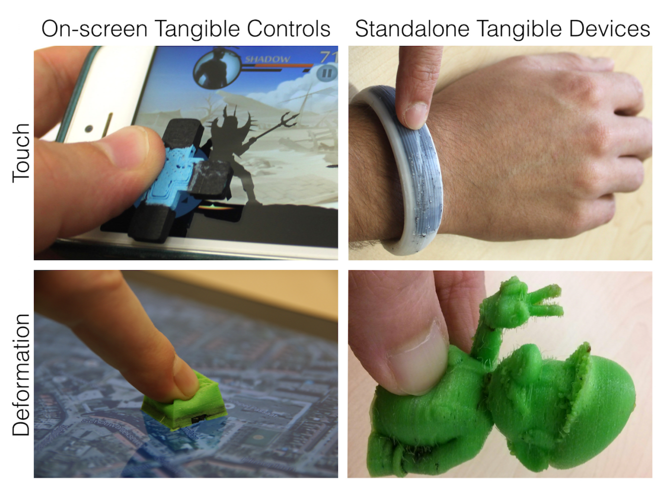

Figure 4: Examples of touch and deformation input in on-screen tangible controls and standalone tangible devices. Black parts are interactive.

adding or removing mass (see Figure 4 at the bottom). Deformation can occur in many different ways, e.g., by pressing, bending, stretching or skewing. Therefore, I will investigate how users can be empowered to easily fabricate 3D objects with integrated deformation-sensitive parts that are capable of detecting various types of deformation.

Towards objective 3. Furthermore, I will investigate tangible interaction concepts for physical 3D objects in two forms: as on-screen tangible controls and as standalone tangible devices. An important question towards this objective is whether there are general interaction concepts for such a broad range of producible 3D objects or whether there are certain classes of 3D objects that share common interaction concepts (e.g., depending on their form or the scenario in which they are used). Here I also want to study what users would like to create with this fabrication environment. As one concrete example, I plan to study deformation-sensitive objects in the domain of assistive technologies, e.g., the fabrication of deformation-aware prostheses for hands, that sense how much the object is pressed in the hand, or for foots, that detect slight deformations associated with walking.

CONCLUSION

In my dissertation, I explore how users can be enabled to easily use 3D printing to create a multitude of interactive tangible objects. I plan to contribute towards three research objectives: First, how can users easily and with least effort design interactive 3D objects? Second, how to automate the fabrication via novel sensing structures and algorithms that work on many 3D printable objects. Third, I want to identify and study tangible interaction concepts for 3D printed objects.

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