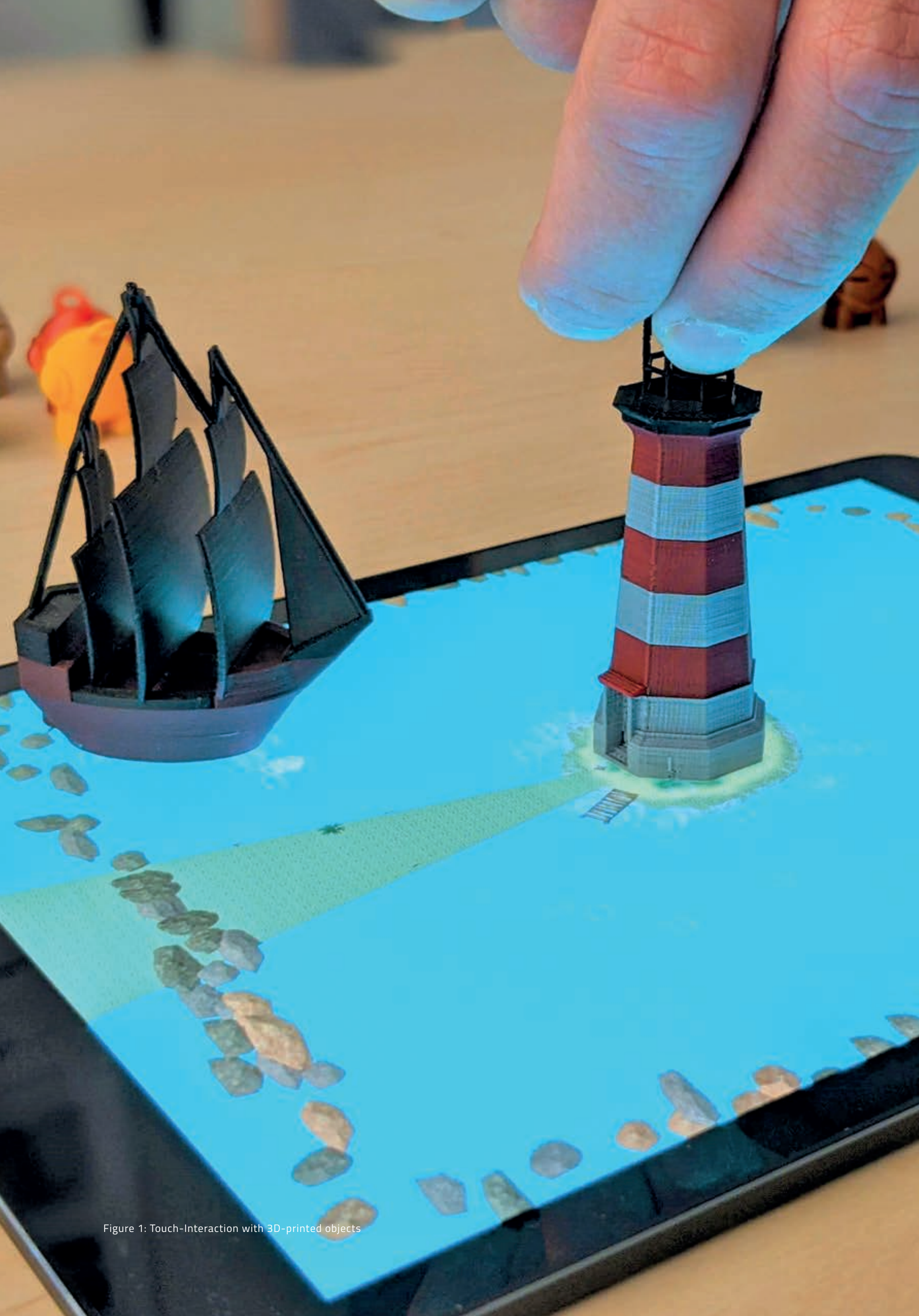

Figure 1: Touch-Interaction with 3D-printed objects

FROM ATOMS TO BITS:
3D-PRINTED HUMAN-COMPUTER INTERFACES

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Abstract

The progressing digitalization increases the demand for interactive devices that bridge the physical and digital world. While there is great potential for customized interactive devices tailored to specific applications or users, until recently, integrating interactivity in custom devices required pre-defined components (e.g., rectangular buttons or flat touchscreens) that constrain the shape of the device.

A more flexible alternative has opened up with the advent of 3D printing which empowers companies, developers, and end-users to design and fabricate custom-shaped individual objects on-demand with relatively low effort. Even though recognized as revolutionizing the manufacturing process, the 3D printing of custom-made interactive devices still requires novel sensor concepts, that operate on complex geometries, and significant design or assembly effort.

Introduction

"Despite our fascination with screens, we still live in the real world. It's the food we eat, our homes, the clothes we wear, and the cars we drive. Our cities and gardens; our offices and our backyards. That's all atoms, not bits." (Chris Anderson, 2012 [1])

For decades information technology aims at increasing digitization by converting previously analogous tasks (such as paperwork or communication) to the digital world. While this conversion is often beneficial, it frequently neglects more subtle information (such as the feel of a book or the non-verbal cues in face-to-face communication), awakening the desire to increase the fusion of digital and real world. This desire manifests in the trends of ubiquitous computing, in which digital technology distributes and blends into the real world, and tangible interaction, in which the physical world provides the means to interact with the digital world. However, the interaction with ubiquitous or tangible devices often does not meet the custom requirements of users or application scenarios. One enabling technology to realize this fusion and at the same time maintain the need for customized interactive devices is 3D printing.

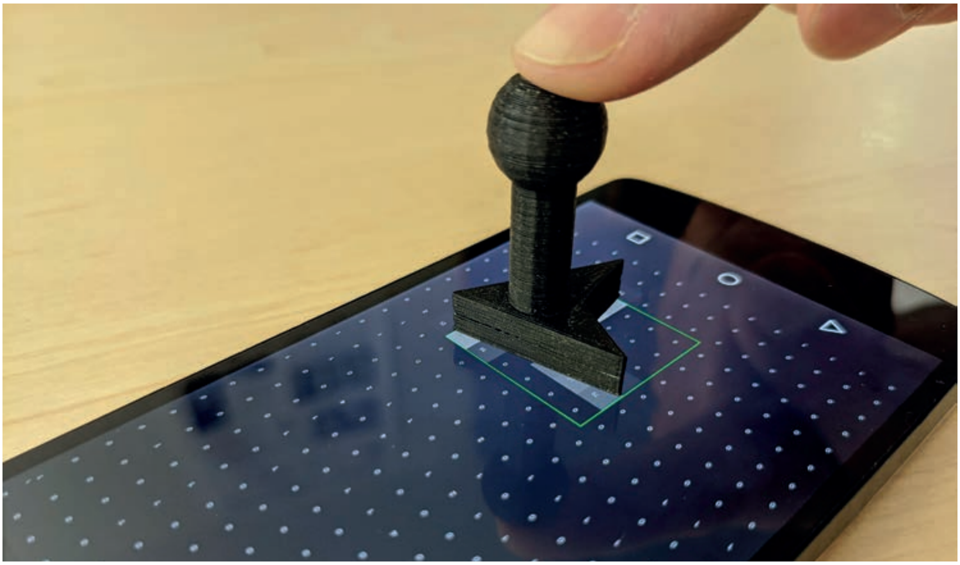


Figure 2: *Itsy-Bits* project: Methods for recognizing the position, rotation, and identity of 3D-printed objects

Figure 3: *./trilaterate* project: Interaction through deformation

Atoms: The Emergence of 3D Printing

3D printing is considered to have the potential to trigger a new industrial revolution [1]. It is intended to enable broad masses of creative developers, communities, or companies to invent new or improved individualized products and to produce them on demand in one step at low cost, even in small series, and, if necessary, to distribute them themselves. Affordable special requirements and individual products as well as a democratization of production offer opposition to uniform mass products of large companies. In the course of this development, open workshops (often called fab labs or maker spaces) with access to 3D printers have emerged worldwide. Even if no industrial revolution will take place, it is mainly undisputed that traditional industrial production will continue to develop in the direction of faster development of prototypes and customized products due to 3D printing.

Bits: The Need for Custom-Made Interactive Devices

Parallel to the development of 3D printing, the demand for *custom-made interactive devices* is continuously increasing in the field of human-computer interaction: information technologies support more and more everyday products and require more product-specific interaction technologies (e.g., touch-sensitive desk lamps or smart kitchen appliances). Research has shown that for specialized tasks or user groups customized interactive devices can offer an improved user experience compared to standard techniques [2]. For instance, more precise [3] or faster [4] data entry is possible with a tangible device instead of a touch-based interface. However, designing and manufacturing product-, task-, or user-specific interactions have so far been very time-consuming and costly. Therefore, custom-made interactive devices remain limited to expensive specialized systems or research prototypes.

The Gap Between Atoms and Bits

Apparently, *3D printing for custom-made interactive devices* can profitably combine both motivating trends. From the perspective of 3D printing, this means that interactive devices could now be individually designed and produced in small quantities. From the perspective of custom-made interactive devices, there is the opportunity to benefit from the cost and effort-reducing effects of 3D printing.

To beneficially combine both trends, it must be possible to *3D print interaction*. That is, a digital blueprint of an interactive device is specifically generated according to custom requirements and automatically fabricated using 3D printing. For example, this combination may enable custom-shaped touch-sensitive surfaces or optical elements that exactly fit the needs of users or application scenarios. Research is currently making significant progress in these directions [5–15].

Custom-made interactive devices can massively change the market if people, research groups, independent designers, or companies are enabled to design, print, and use interactive devices specifically made for their use case with minimal effort. However, considerable progress is still required before the benefits of 3D printing can be fully applied to custom-made interactive devices. This progress includes improvements concerning a more user-friendly design, interactive structures that apply to a wide range of 3D geometries, and algorithms that generate and precisely fit such structures in 3D geometries.

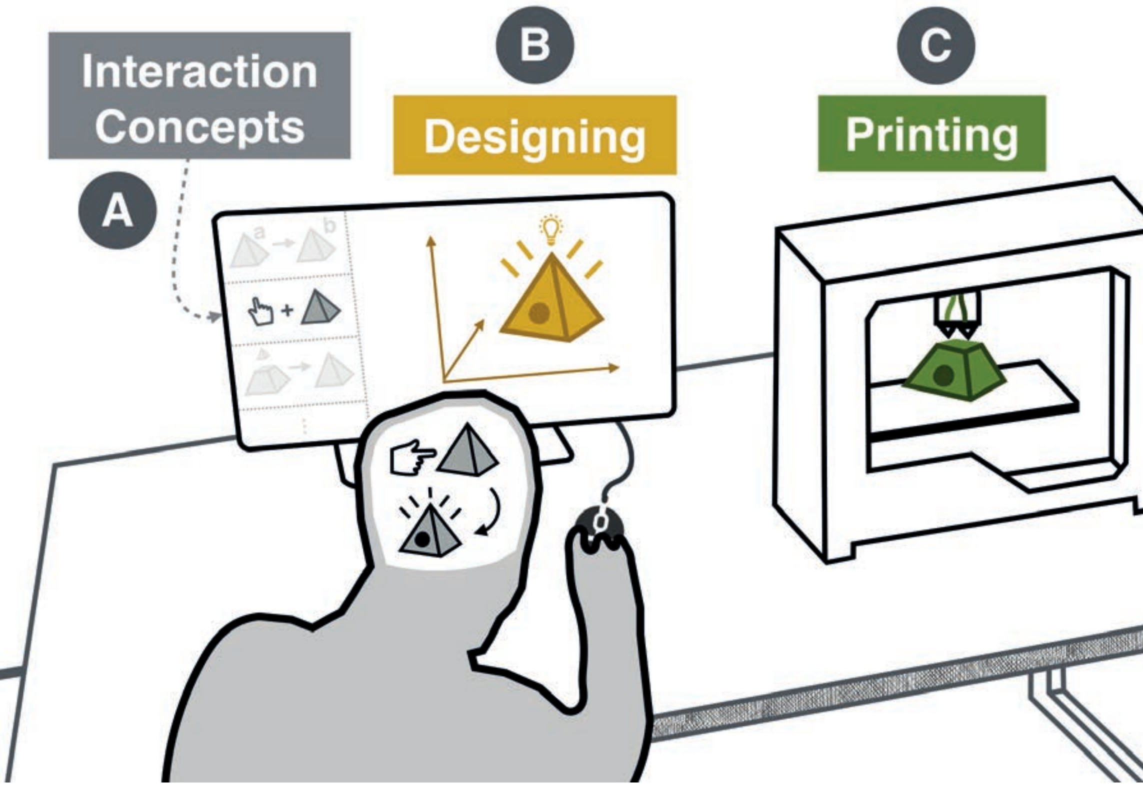


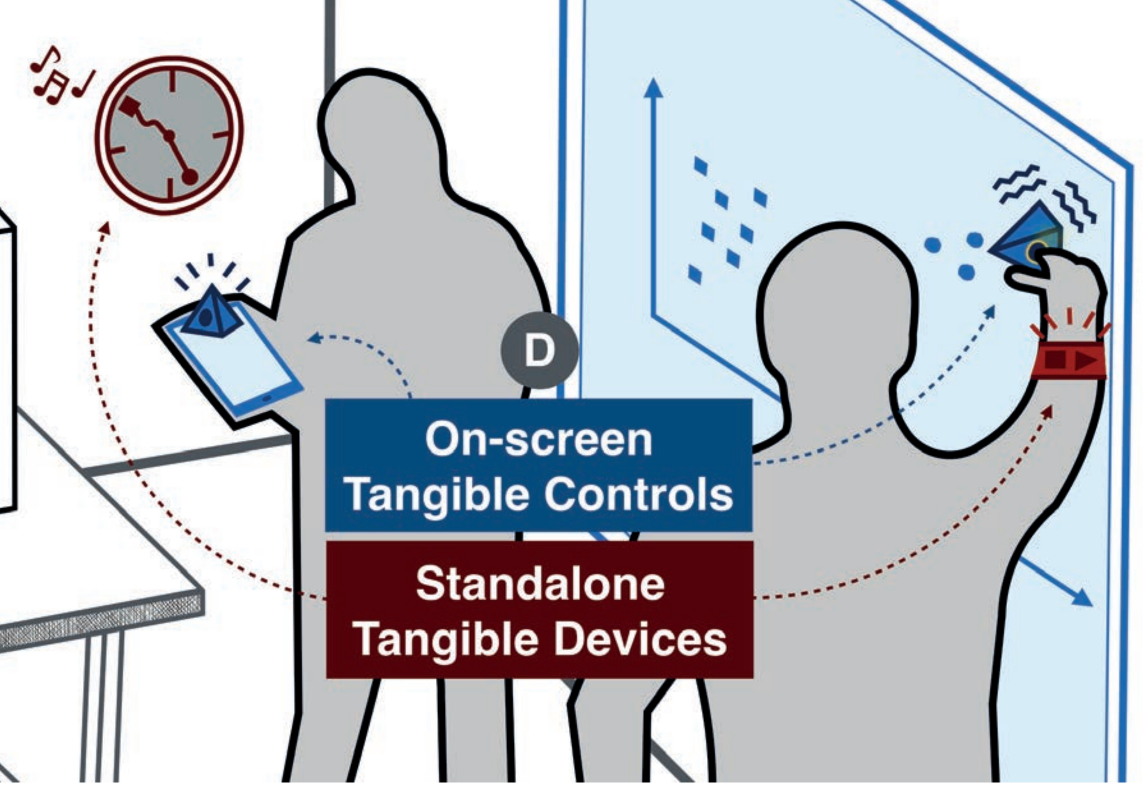
Figure 4: The envisioned fabrication environment to create custom-made interactive devices (based on [8]).

Towards 3D-Printed Custom-Made Interactive Devices

The vision of creating 3D-printed custom-made interactive devices is as follows: Like today's desktop 2D printers, 3D printers will be fast, cheap, reliable, and widely available in almost every home or a professional 3D printing store. Instead of mass production, users fabricate many objects on-demand in varying shapes, colors, and materials without the need for excessive post-processing. Inspired by this general vision of 3D printing, we envision a potential *future fabrication environment for interactive devices* that enables researchers, application developers, and also end-users without skills in computer-aided design to equip a selected 3D object with user-defined interactivity. As illustrated in Figure 4, this environment builds upon tangible interaction concepts (A), such as *touching* or *moving* an object. Users express their ideas in a digital design phase by adding various interactive structures to a 3D object (B). They can then fine-tune properties such as the desired size or resolution of the interactive structures. Users then (possibly repeatedly) 3D print their custom-made interactive object at home or a 3D printing

store (C) and use it (D) either as a tangible *stand-alone device* (red) or as an *on-screen control* (blue) that interfaces with commonly-used touchscreens (e.g., a smartphone, tablet, or wall-sized display).

This fabrication environment should be as natural and automatic as today's creation of paper documents using



word-processing software and a 2D desktop printer. For instance, end-users combine it with 3D scanning to adjust wearable devices to their body dimensions, to design entirely new interactive devices on top of existing objects, or to customize home appliances pre-designed by a company to their needs.

Addressing the Challenges

Towards this vision of easy and automatic fabrication environments, research needs to resolve numerous challenges: One research challenge concerns the exploration of *interaction concepts and primitives* for custom-shaped interactive structures, specifically tailored for the complex geometries of 3D-printable objects. Another research challenge involves *algorithms that generate such structures* on or in the 3D object since manual design today is lavish, requires considerable expertise, and is prone to errors. Moreover, the design of interactivity and the 3D geometry of the object are separated, i.e., fixed-form standard components (e.g., a flat display panel) are attached to or embedded into non-functional, passive 3D objects that have been mass-produced. Therefore, another research challenge is the investigation of *novel design concepts* that enable users to embed interactive free-form 3D structures at the design phase.

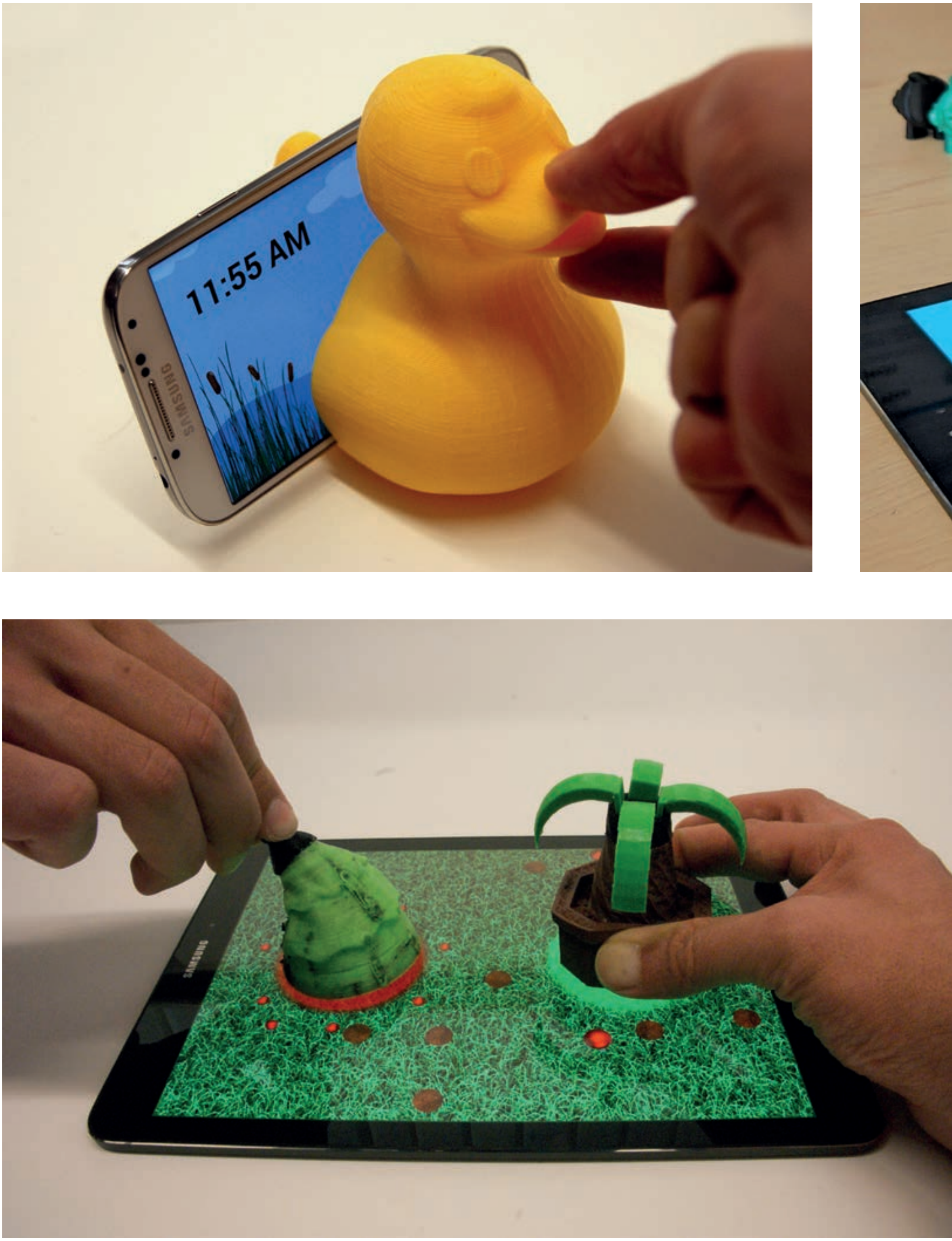
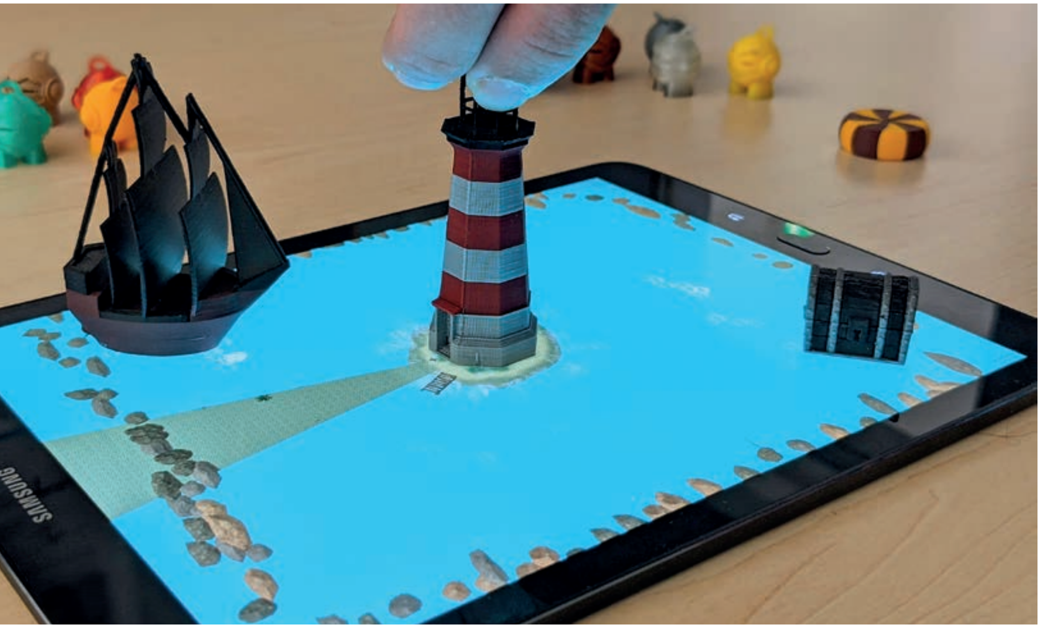


Figure 5: A set of examples illustrating the interaction with 3D-printed objects via touch (top), deformation (bottom left), or the environment (bottom right).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These challenges can be considered for different styles of interaction:

Touch Interaction

Since its everyday use in smartphones or tablets, touch interaction has become one of the most common forms of input along with mouse and keyboard. It enables more direct operation since interfaces can be touched directly and do not have to be controlled indirectly, as with a mouse or keyboard. However, touch recognition is often limited to simple flat surfaces and rectangular flat shapes (e.g., the display of a smartphone), making it conceptually and technologically difficult to integrate into 3D printing. As part of the *Capricate* project [9], we, therefore, have investigated opportunities for 3D printing sensor technology and electrodes that can be used for touch detection (see Figure 5 top left). To this end, we developed a fabrication pipeline that supports the digital creation, export, and subsequent 3D printing of touch-sensitive objects on low-cost 3D printers. In addition, we have developed algorithms that enable the detection of touch not only on flat surfaces but also on highly curved surfaces.

Furthermore, 3D-printed touch-sensitive objects in combination with tablets or larger touch displays can form a new kind of *tangible* interface that combines physically touchable objects with digital visual content. In the *Itsy-Bits* project [10], we have therefore contributed methods for recognizing the position, rotation, and identity of 3D-printed objects on commonly-used touchscreens (see Figure 5 top right). This approach can create a variety of new tangible user experiences that are no longer limited to mass production but also enable highly individualized user experiences (for example, custom game characters in a digital tangible game or interactive house models on a city map).

Deformation Interaction

Complementary to touch interaction with 3D-printed objects, deforming an object itself for interaction is another promising research direction as it adds another haptic input dimension. In general, *deformation* can manifest in a variety of ways, for example, pressing

Figure 6: Interaction with deformable 3D-printed objects

into the surface, bending an entire subpart of an object, or squeezing it with the thumb and index finger. While touch input is in general binary (i.e., either an object is touched or not), deformation input holds the potential for a more continuous way of providing input to computers by varying the strength applied during the deformation. To investigate this research direction, the *Flexibles* project [11] and the *./trilaterate* project [12] have contributed sensing structures and algorithms to detect various deformations either via an attached microcontroller as a standalone tangible device or in combination with standard touchscreens commonly used in today's smartphones and tablets (see Figure 5 bottom left).

Environmental Interaction

The detection of influences from the environment is another important category in interactive systems. In particular, the increasing production of 3D-printed objects offers great potential for embedded sensor technology, as time-consuming and cost-intensive assembly steps are minimized. However, such sensing systems often still require an energy source. In the projects *Off-Line Sensing* [13] and *Liquido* [14], we have, therefore, explored mechanisms that can detect a change in the state caused by an external influence (for example, the shaking or tilting of an object, or a change in environmental temperature) and record it *irreversibly* in the object structure without requiring any power source (see Figure 5 bottom right). Whether the state of such an object has changed can be read out through an app on a standard touchscreen. Such mechanisms could, for example, be integrated directly into building components to provide low-term information about changes in important parameters (for example, the exceeding of load limits) without power requirements. Building on this principle, the *3D-Auth* project [15], for example, has used such state changes as a second factor for authentication with 3D-printed objects.

Conclusion

3D printing holds the potential for a revolution, as it offers the possibility to individually manufacture very complex structures. In addition to a plethora of applications in mechanical and building engineering, the production of interactive objects, which are already increasingly finding their way into everyday lives, can, with the help of this technology, also be made more user-friendly, more individual, and more precisely tailored to the respective individuum and application. This opens up the opportunity to move away from the mass production of uniform interaction devices to a world in which interaction with computers is tailored to the needs and capabilities of each individual. The projects presented in this paper are one of the first steps toward this vision, whose potential is far from exhausted.

Acknowledgments

Parts of this paper have been previously published by the author [8].

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