Toward Highly Interactive Custom Objects Using Printed Electronics

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Abstract

3D printing allows users to easily create objects with highly customized geometries. However, these typically lack interactivity. Printed electronics is a complementary technique that, when combined with 3D printing, enables fabrication of highly interactive objects. Based on our experiences from a recent research project, we outline cross-disciplinary challenges in fabricating custom interactive objects. Progress toward solving these challenges requires research at the intersection between HCI, computer graphics, material science, design, and engineering.

Author Keywords

3D printing; 3D modeling; prototyping; fabrication; tangible interaction; shape change; printed electronics.

ACM Classification Keywords

H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous

Introduction

Digital fabrication is enabling end-users to easily and rapidly create objects with highly customized geometries, by using techniques such as computer-controlled cutting, milling, or 3D printing. However, these objects are typically static in a sense that they offer limited interaction possibilities. To go beyond pure mechanical reconfiguration and to add an

interactive user interface, electronic components are essential. For this purpose, recent research has proposed embedding off-the-shelf components inside 3D-printed objects [9] or attaching fabricated objects to consumer electronic devices [5, 12]. An even greater design freedom is offered by rapidly advancing printed electronics technologies. They allow, for example, to easily print custom circuits using inexpensive inkjet technology [4]. This method has been used extensively by HCI researchers to fabricate custom 2D interfaces, e.g., [6, 2, 8]. Beyond conductors, a variety of electronic components can be printed, including thin-film displays, solar cells, or batteries.

Advancing toward fabricating interactive 3D objects, novel materials have been used for 3D-printing of simple conductive traces. These allow, for example, to add capacitive touch sensing to 3D-printed objects [10]. However, the range of functional materials that is available for 3D-printed electronics is much smaller than for printing on flexible 2D substrates. In addition, the electronic characteristics of 3D-printed electronics are way inferior; it is hard to predict when and if at all they will achieve similar capabilities. This makes 2D-printed electronics a very interesting choice for fabricating interactive 3D objects. As demonstrated by Olberding et al., interactive 3D objects can be quickly and easily prototyped by folding 2D-printed electronics [7]. Our recent work HotFlex [3], on the other hand, demonstrates that 2D-printed electronics can be successfully embedded within 3D prints, enabling computer-controlled state-change in 3D objects. During our work on HotFlex we identified three major cross-disciplinary challenges in fabricating custom interactive objects. In the following, we will briefly present HotFlex and then discuss these challenges.
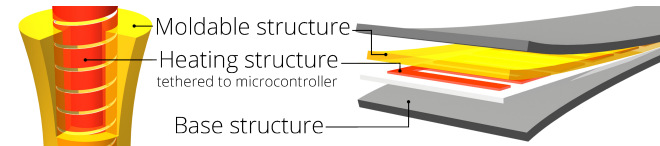

Figure 1: The HotFlex printed material composite consists of three structures. They can be realized as volumes (left) or thin layers (right). (from [3])

HotFlex: Post-print Customization of 3D Prints Using Embedded State Change

HotFlex [3] is a new approach that allows precisely located parts of a 3D-printed object to transition on demand from a solid into a deformable state and back. It enables intuitive hands-on remodeling, personalization, and customization of a 3D object *after* it is printed (see Fig. 2).

The approach is based on embedding computer-controlled elements inside the object. These elements essentially consist of heating elements, printed with conductive materials, and surrounding structures, which are printed with a material that has a low melting point (see Fig. 1). When the element is warming up, the surrounding material becomes viscous: the user can deform it. This approach can be used to achieve an expansive range of post-print customizations, including very localized on-demand modifications and creation of shapes of high mechanical stability. In addition, it can be implemented using conventional printers and off-the shelf hardware components.

In our paper, we present a set of functional patterns that act as building blocks and enable various forms of hands-on customization. Furthermore, we demonstrate how to integrate sensing of user input and visual output.
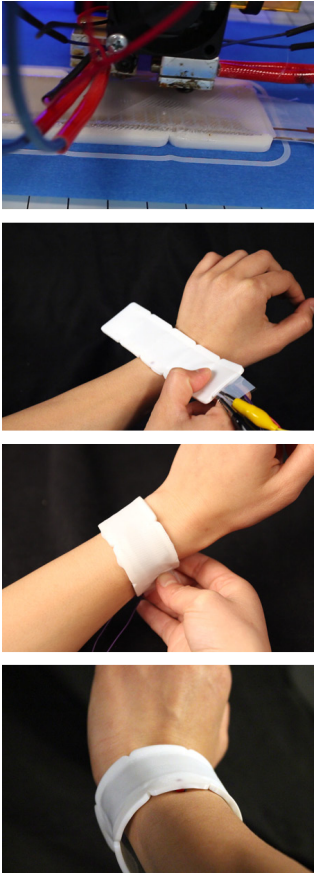
Figure 2: A 3D-printed object with embedded state-changing elements. The end-user can physically customize the object on-demand after it is fabricated. (adapted from [3])

Cross-fab challenges

During our work on HotFlex we identified the following major cross-disciplinary challenges: 1) new materials for printed electronics, 2) easy-to-use design tools which abstract from the technical complexity of embedded circuits, and 3) how printed electronics influence the design and fabrication process.

3D-printed electronics

3D printing of electronics and functional structures (e.g. for internal state-change) requires novel materials with unique properties. While these new materials offer new possibilities, they also present unique challenges for fabrication:

Multi-material printing: As we developed HotFlex we were confronted with limitations of current materials and 3D printers. By exploring new ways of combining different materials and printed electronics, we identified challenges in the printing process of interactive objects. For example, the number of different materials that can be used simultaneously during one print are usually limited to 1-3. This number should be increased to realize the different HotFlex layers and support material in one print pass. But also printing materials with different printing properties is a challenge. Materials with different melting points, for example, require special cooling and modified printing paths. These challenges may be solved by new material formulations or improved 3D printers. The set of requirements should be identified in a reciprocal research effort between HCI and material science and electrical/mechanical engineering.

Printable conductors and functional materials: Current FDM-printable conductive filament suffers from very low conductivity (around $6\ S/m$, compared to copper $58.5\ MS/m$ and 2D-printed silver ink around $16\ MS/m$). This complicates and often even prevents applications, such as sensing or joule heating. Future 3D printers promise to al-

leviate this issue (Voxel8 [11], around $2\ MS/m$), while 2D-printed elements are a viable short/mid-term solution, as done in HotFlex. Other challenges are even more difficult to solve. This involves developing 3D-printable electronically functional materials beyond simple conductors. For instance, this includes transparent conductors, dielectric, semiconductors, or light-emitting functional materials. Moreover, with objects being printed from flexible and stretchable materials, embedded electronics need to possess these properties, too. For HotFlex we found this to be a limiting factor in designing customization patterns. We had many concepts beyond what we were able to implement. From this, we conclude that we can provide valuable input on the requirements for these materials by exploring their use for fabricating human-computer interfaces.

Appearance and esthetics: Printed electronics may not only serve functional purposes but also influence the appearance and esthetics of an object. When circuitry cannot be hidden but is visible on the surface, one must not only accommodate for the geometric constraint posed by embedded electronics but also for visual requirements. Designers and artists will benefit from support regarding geometric constraints, such as the maximum wire length or minimum trace width that depend on materials and functionality. In turn, their knowledge on visual requirements helps to further explore how electronics can be best integrated into 3D objects.

UI builder for interactive objects

The design of passive 3D objects is a difficult task already. When introducing electronics and functional structures, even more expert knowledge is required. During design of HotFlex patterns we were faced with this challenge. The structures consisting of multiple layers and printed heating elements offer many degrees of freedom. To facilitate

integration of HotFlex functional patterns into designs we implemented our patterns as parameterized scripts that can be easily adjusted. However, this still requires skill for integrating patterns in complex objects.

To further ease design of interactive objects, design tools need to abstract from complexity and automatically generate lower level details. For electronic components that means primarily to provide the user with an inventory of interaction components and to automatically generate the underlying circuitry [6, 8]. For 3D objects this also involves generating function structures embedded in the object's geometry [1].

Design and fabrication process
The HotFlex approach illustrates that embedding printed electronics does not only have an impact on what can be printed, but also influences the fabrication process itself. The ability to modify objects after they have been printed, partially shifts the design and fabrication process into the use phase. This creates a new open space for novel "self-contained" fabrication and customization methods, which do not require any tool besides the object itself. This space should be further explored with domain experts in design and art.

Conclusion
Printed electronics open up a large space of possibilities for fabricating interactive 3D objects. We would like to encourage the HCI community to explore this space and to think about how these technologies can be used for digital fabrication. This way, the HCI community can provide valuable input to material scientists and engineers on what future materials and fabrication processes are required. In turn, HCI will directly benefit from new developments in material science and engineering. In addition, we will benefit from cross-disciplinary research toward easy-to-use design tools that address the challenges of printed electronics. These will enable designers and end-users to easily create interactive 3D objects using printed electronics.

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