Envisioning, designing, and implementing the user interface require a comprehensive understanding of interaction technologies. In this forum we scout trends and discuss new technologies with the potential to influence interaction design. **— Albrecht Schmidt, Editor**

Printed Electronics for Human-Computer Interaction

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A technology revolution is happening. For a long time, electronic components were accepted as being rigid, rectangular, and somewhat bulky. As a consequence, today's computing devices are typically flat, rectangular, and have a fixed shape. But a new technology is challenging this established view. Printed electronics offers a new way to realize fundamentally different electronic components that are paper-thin and deformable, that can cover large areas, and that can be deeply embedded within various materials and geometries.

These new possibilities have already been influencing HCI research and consumer electronics through flexible OLED and e-paper displays. Research such as Gummi, Nokia Kinetic, PaperPhone, and Flexpad has investigated new interactions for handheld devices that can be physically deformed.

Now printed electronics itself is becoming accessible as a tool for HCI researchers, makers, and even interested laypeople. Recent work in printed electronics is enabling non-experts to print their own functional devices and interactive surfaces in a way that's very similar to printing graphics on paper. Ready-to-use printing techniques are available to produce your own customized sensors and displays easily, rapidly, and at low cost. The hardware can be controlled with common DIY hardware platforms such as Arduino.

This is opening up exciting new possibilities for HCI, as it is now possible to realize interfaces that so far designers might have conceptualized but would not have been able to implement. For instance, radically new types of mobile and wearable interfaces can be implemented by printing touch-sensitive display surfaces of custom shape that are very thin, lightweight, and deformable. These can be handheld, worn right on the human body, or integrated within clothing, interactive jewelry, and accessories. Printed on paper, electronic components can realize smart packaging and interactive paper solutions for new interfaces in education, knowledge work, communication, and play.

Furthermore, new geometries and new materials make it possible to deeply embed user interfaces within the physical environment. Printing on very large surfaces enables interactive floors or interactive wallpaper. Printing on curved surfaces enables smart objects and applications in the car. And printing electronics on wood can realize aesthetically pleasing, calm interfaces that are embedded within furniture.

Insights

→ Printed electronics enables HCI researchers, makers, and end users to print their own customized user interfaces.

→ Recent research in HCI has contributed platforms and toolkits for easy, rapid, and inexpensive printing of electronics.

→ The technology can enable radically novel interfaces and interactions in mobile, wearable, tangible, and embedded computing.

PRINTED ELECTRONICS IN A NUTSHELL

Printed electronics involves leveraging conventional printing methods together with new types of inks to fabricate electrical devices. It benefits from the long history of graphic printing, which over the years has led to a wide range of printing methods that produce very high-quality prints, are extremely cost-efficient, and can print in low to high volume. And of course they are compatible with all kinds of flexible and rigid substrates, including inexpensive paper or transparent polymer films, but also more unconventional materials such as wood, stainless steel, ceramics, fabric, and leather. Pretty much any established printing method for graphical printing has been successfully used for printing electronic components. This includes roll-to-roll mass printing methods, very versatile screen printing, and fully digital inkjet printing, which is very well suited for low-volume printing. Thus far, the field is mostly focusing on 2D printing on thin-film substrates. However, promising work is emerging that allows us to 3D-print electronics within objects, such as the 3D printer of the Harvard spin off Voxel8.

The key to printed electronics is the electrically active inks and pastes, a very dynamic research

Figure 1. Using a consumer-grade inkjet printer to print a conductive circuit on photo paper [1]. (Courtesy of Yoshihiro Kawahara)

area. Already a wide range of inks with various electrical properties are commercially available. Depending on the material, a printed structure can act as conductor, semi-conductor, isolator, or dielectric. It can also exhibit other functional properties, such as actively emitting light. Commonly used materials include dispersions of metallic or carbon particles (e.g., silver nanoparticles) and conductive and semi-conductive polymers (e.g., PEDOT:PSS and pentacene).

The functional behavior is defined by not only the material, but also the geometry in which one or multiple materials are printed. A conductive structure printed on a single layer can act as a flexible circuit board, as well as a resistor, capacitor, inductor, or antenna. By printing various materials on multiple layers, active components can be realized such as displays, more complex sensors, actuators, transistors, and batteries.

Will the next generation of microprocessors be printed? Will printed electronics replace conventional silicon-based electronics? No. Rather, printed electronics will coexist with them. Printed electronics is limited by a much lower integration density due to the lower resolution of printing. It also offers considerably lower switching times than in conventional electronics because of the low mobility of printed semi-conductors. Therefore, we will see continued use of conventional electronics for high-performance applications, while printed electronics will open up new markets and applications for thin, lightweight, large-area, deformable, and extremely low-cost electronics.

PRINT YOUR OWN FUNCTIONAL USER INTERFACE

So why not use printing to prototype your new mobile, wearable, tangible, or embedded user interface? In ground-laying work, Kawahara et al. [1] have demonstrated that highly conductive structures can be printed in high resolution with a consumer-grade inkjet printer, which is as cheap as $100. The approach replaces the standard inks in the cartridge with commercially available conductive ink, which is made of silver nanoparticles. The user designs the conductive traces and electrodes in any graphics application and then prints them within a few seconds on a specific type of photo paper (Figure 1). Despite its limitation to single-layer printing, the method can be used for a wide variety of purposes. Among other scenarios, the authors have demonstrated its efficacy in the rapid prototyping of deformable electronic circuits and for printing capacitive touch sensors and RFID antennas.

If the prototype requires more complex functionality that cannot be printed, conventional electronics components can be attached onto the printout by using CircuitStickers, which the authors have presented in follow-up work. The team has also contributed an improved multimodal sensing technique [2]. It allows for single-layer printing of sensors that are capable of sensing multi-touch and proximity input, several levels of touch pressure, and deformation. Last but not least, printed sensors can be visually appealing, as shown in Figure 2.

Other conductive inkjet printers can realize much larger circuits by printing onto material dispensed

Figure 2. Printed circuits can be both functional and aesthetic. This is a capacitive sensor for music control on an electric ukulele, adapted from an artwork by Evgeny Kiselev. (Courtesy of Nan-Wei Gong)

Figure 3. This multi-touch sensor sheet is cuttable into various shapes and remains functional. This enables physical prototyping of electronic components [4].

from a roll. This enables new kinds of large-scale interfaces, for instance, smart wallpapers and floors that offer embedded sensing and output capabilities. Gong et al. have contributed a large-scale sensor floor, which was realized on a several meter long flexible substrate [3]. The sensor can be deployed on or under a floor to detect the presence and whereabouts of people.

In addition to deformability and large sizes, printed electronics offers new affordances that can be leveraged for interaction. One such affordance is that thin sheets are cuttable. This allows for very direct and instant physical customization. Why not simply cut a sensor film to a desired shape in order to augment a physical object or surface with touch-sensing capability? Olberding et al. [4] have contributed a cuttable multi-touch sensor that remains functional after it is cut into a new shape (Figure 3). The printed sensor ensures resilience to cutting by new geometric layouts in which the individual electrodes of the sensor are connected to the controlling unit. Given the low cost of printed electronics, it's conceivable that it will be possible to buy touch-enabled materials that can be used pretty much as if they were conventional materials, supporting rapid and hands-on prototyping of electronics.

More complex sensors can be realized using multi-layered printing and additional functional materials. PyzoFlex [5] is a thin pressure-sensing foil that exhibits a very linear response and therefore allows for continuous measurement of normal force. The sensor is screen printed in several layers. Its functional layer is made of a new pyro- and piezo-electric material, which is not yet commercially available. In follow-up work called FlexSense, the authors have used the same functional material to realize a mostly transparent and very accurate deformation sensor.

While most prior work on printed electronics in HCI has investigated sensors for capturing user input, new work is addressing the output side. PrintScreen [6] is a platform that enables non-expert users to design and fabricate light-emitting and touch-sensitive displays (Figure 4). The approach leverages commercially available electroluminescent ink, which emits light when a current is applied. This is closely related to OLEDs, the difference being that electroluminescent displays require a higher voltage but can be fabricated in ambient environments without the need for a cleanroom. PrintScreen displays can be printed either with conductive inkjet printing, which is very fast, or using hobbyist-level screen printing, which supports more complex displays. The displays are around 0.1 mm thin, deformable, and highly customizable, not only in terms of content but also in terms of shapes and materials. Among other materials, displays can be printed on paper, transparent polymer film, wood, leather, ceramics, and steel. PrintScreen enables the prototyping of new kinds of mobile, wearable,

Figure 4. Some examples of deformable touch-sensitive displays fabricated with PrintScreen [6].

and ubiquitous computing interfaces, including customized interactive print products, smart packaging and objects, personalized body-worn interactive accessories, and crafts with embedded displays.

All approaches presented here realize the input/output surfaces with printed electronics, while the controlling unit and battery are still conventional components. Paper Generators [7] presents a way to realize flexible interactive surfaces with a self-contained energy supply. Paper Generators harvest energy from the user's interaction with the interface. For instance, when tapping on a button, the user unconsciously generates the energy required for the interface.

WHAT IS DOWN THE ROAD?

The fabrication approaches presented here are affordable for most any HCI lab, maker space, or even private hobbyists. This opens up new creative ways of exploring electronics and new types of user interfaces, new interaction modalities, and applications. However, using consumer-grade printers and simple controlling electronics comes at a cost: limited resolution of sensors and displays as well as continued need for rigid electronic components.

These current limitations are fully acceptable for the purposes of prototyping and even for a wide range of commercial applications. But the good news is that printed electronics can already offer much more than what has been explored in HCI thus far. The state-of-the-art in printed electronics is rapidly advancing through contributions in chemistry, material science, and printing technology. It is also a very dynamic market; the first commercial products have already been released, and many more are waiting in the wings. A good overview of the state-of-the-art is provided in [8].

In terms of displays, high-resolution flexible displays are entering the market. Curved OLED displays have already been deployed in consumer electronics, for instance, in curved smartphones and curved TVs. Deformable displays, including foldable and even rollable ones, are predicted to be commercialized in the near future. The most recent trend in printed displays looks beyond just deformable displays into displays that can be stretched, for instance, when printed onto textiles and other elastic substrates.

In terms of sensors, many more modalities than touch, pressure, or deformation can be realized using printed electronics. This includes environmental sensors for temperature, pressure, and humidity, sensors for chemical analyses, light sensors, as well as biosensors. These sensors will enable a wide range of applications in areas such as health, environmental monitoring, and quality checking. First products, such as printed glucose test strips, have become commercially available.

To make the entire device thin and flexible, and not just the input/output surface, additional components need to be printed: logic, memory, and battery. The first printed flexible batteries have become commercially available, and so have flexible solar cells, which could charge mobile devices and one day even cover the roofs of cars. Also, simple logic circuits and printed memory have been successfully demonstrated as prototypes. While they are still very far from having the processing power of conventional electronics, they could soon enable specialized applications such as smart packaging, fully printed RFID tags, or smartcards that incorporate processing and some display output.

These few examples show that a user interface prototyped using the methods described here can be brought to a whole different technical level when it is mass-produced with commercial high-end fabrication techniques. These recent advances also make it very likely that in the near future an increasing variety of components can be printed in do-it-yourself setups and through specialized low-volume print services.

Even though it is challenging to predict the market in this young and disruptive field, one thing is clear: Printed electronics empowers us to realize applications of electronics that were unthinkable before. Let's embrace this new technology to realize a new generation of user interfaces that are thin, lightweight, expressive and aesthetic, and deeply embedded in our physical environment.

Endnotes

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DOI: 10.1145/2754304