PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays

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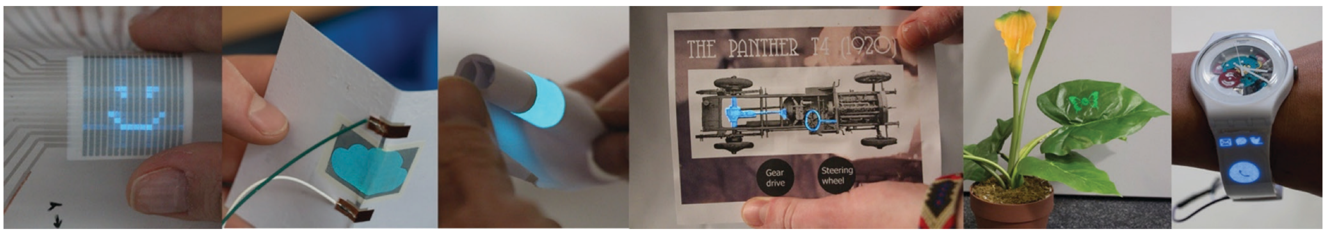

Figure 1. PrintScreen contributes a digital fabrication approach to enable non-experts to print custom flexible displays. They can be fully folded or rolled and enable manifold applications in ubiquitous, mobile and wearable computing.

ABSTRACT
PrintScreen is an enabling technology for digital fabrication of customized flexible displays using thin-film electroluminescence (TFEL). It enables inexpensive and rapid fabrication of highly customized displays in low volume, in a simple lab environment, print shop or even at home. We show how to print ultra-thin (120 µm) segmented and passive matrix displays in greyscale or multi-color on a variety of deformable and rigid substrate materials, including PET film, office paper, leather, metal, stone, and wood. The displays can have custom, unconventional 2D shapes and can be bent, rolled and folded to create 3D shapes. We contribute a systematic overview of graphical display primitives for customized displays and show how to integrate them with static print and printed electronics. Furthermore, we contribute a sensing framework, which leverages the display itself for touch sensing. To demonstrate the wide applicability of PrintScreen, we present application examples from ubiquitous, mobile and wearable computing.

Author Keywords
Flexible display; Thin-film display; TFEL; Electroluminescence; Printed electronics; Digital fabrication; Rapid prototyping; Touch input; Ubiquitous Computing.

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INTRODUCTION
Printed electronics is becoming a powerful and affordable enabling technology for fabricating functional devices and HCI prototypes that have very thin and deformable form factors. For many years already, printing has been a powerful means allowing end-users to produce customized *static* print products rapidly, inexpensively and in high quality. Recent work has contributed methods for easily printing custom *interactive* components on thin and flexible substrates. While sensing of user *input* has been successfully demonstrated [7, 13], it has not been possible so far to print customized flexible *displays* rapidly and inexpensively. Printing flexible displays, such as OLEDs or Electronic Paper, required a high-end print lab, complex machinery and expert skills, making it prohibitive to fabricate custom displays in low volume.

We present PrintScreen, a versatile platform that enables non-expert users to design and fabricate highly customized flexible interactive displays. The displays are technically based on thin-film electroluminescence (TFEL).

The platform proposes a novel perspective on displays: instead of buying an off-the-shelf display, the designer can create a custom digital design, which meets the specific demands of the application, and then simply print the display. Printing customized flexible displays empowers makers and designers to create customized interactive print products, digital signage, smart objects, personalized computing devices and crafts with embedded display. For HCI researchers and practitioners, this is a powerful enabling technology for mobile, wearable and ubiquitous computing interfaces. It enables rapid and high-fidelity prototyping of functional HCI devices with embedded displays of highly custom shapes, on deformable and on unconventional materials.

Based on a holistic five-dimensional view on customized displays, we present the following main contributions:

1) We present *two methods for non-expert printing* of customized thin-film displays, using either screen printing or conductive inkjet printing. The approach is rapid, inexpensive, and does not require much hardware nor technical knowledge. Despite the restrictions stemming from manual fabrication, the display features a high luminance, is only 120 µm thick, bendable, fully rollable, and even foldable at arbitrary positions. It can contain custom-defined high-resolution segments (resolution of contours comparable to 250 dpi laser print) and/or a low-resolution passive matrix (up to 30 pixels per inch). Each segment or pixel can have a color defined at design-time from a wide palette of possible colors. At run-time, it has adjustable brightness intensity. We show that the display can be printed on a *large variety of substrates*, such as paper, plastic, leather or wood, making it ideal for mobile, embedded and wearable applications. PrintScreen can be used to fabricate displays of *irregular and unconventional shapes,* including 2D shapes, folded 3D shapes and adaptable shapes.

2) We propose a digital design approach for displays, which is based on conventional 2D vector graphics. We contribute the first systematic overview of *display primitives* for user-printed displays, which act as basic building blocks in the graphical design. Moreover we show how to integrate printed display primitives with static printed artwork and with printed electronics.

3) We contribute a *sensing framework*, which allows using the printed TFEL display itself for a variety of input sensing. We demonstrate this principle for integrated touch sensing.

To demonstrate how PrintScreen can be used and to show its wide applicability, we present five *example applications* from ubiquitous, mobile and wearable computing. Results from a technical evaluation show that the displays are bright and very robust to bending and folding. We conclude by discussing benefits and limitations of PrintScreen.

RELATED WORK

Digital Fabrication of Electronics

An emerging body of related work is demonstrating the potential of printed electronics for applications in Human-Computer Interaction. Midas [30] introduced a platform for fabricating custom circuits to sense touch input, based on vinyl cutting. Kawahara et al. [13, 14] introduced conductive inkjet printing with an off-the-shelf printer as an instant means for printing customized sensors and antennae. This approach was also used for flexible multi-touch sensor sheets [7, 14]. Pyzoflex [27] leverages printed piezoelectric elements to capture pressure and temperature on a thin sheet. Poupyrev et al. [12] have shown how printed conductors can capture user-generated energy. This body of previous work did not address visual output.

Thin-film Display Technologies

Organic light emitting diodes (OLEDs) and electrophoretic displays (electronic paper) can be printed on flexible substrates. Both technologies enable high-resolution displays, in addition OLED displays support a wide color spectrum. However, they are still complicated to produce. For instance, an OLED display typically requires six layers [15]; moreover it is very sensitive to oxygen during fabrication and requires proper permanent sealing during use. Therefore, a high-end print lab environment is required. While rollable and fully foldable OLED and electronic paper displays have been demonstrated as prototypes, they are not commercially available yet.

Thermochromic [19] and electrochromic [3] displays are less complicated to manufacture. However, they have very long switching intervals and precise control of thermochromic displays is challenging, as the ink is influenced by the ambient temperature.

Electroluminescent (EL) displays are very robust, have fast switching times and a long lifetime of up to 50,000 hours [6]. Therefore the technology is often used for lighting applications [4, 21]. Inspired by [4, 35], we propose electroluminescence for custom-printed displays. The technology, a simple form of OLED, is based on phosphoric inks, which act as luminescent material. The print process requires only 4 layers [15]. Recent chemical advancement allow for inks that can be easily processed and need low curing temperatures. EL displays require higher AC voltages but very little current to operate. Previous work proposed creating simple EL displays by cutting out segments from an EL film [2]; in contrast, our approach relies on high-resolution printing and therefore enables fabrication of a much wider spectrum of displays.

A substantially different approach is based on 3D printed optics [36]. Printed light pipes transmit light from a conventional rigid display to custom points on the surface of a 3D printed object. This allows for easily designing 3D shaped displays of custom shapes, supporting full color and a high resolution. However, designed for 3D printing the approach is not compatible with thin-film form factors, since the printed optical elements need some volume.

Applications of Deformable and Custom-shaped Displays

A body of work demonstrates the need for objects that are augmented with interactive displays of different size and shape [10, 16, 23, 24, 34, 37], resolution [9, 24] and substrate [24]. One stream of research proposes deformable displays of various shapes and sizes for use in mobile and wearable contexts [5, 17, 20, 25, 31, 33, 37, 29]. Another stream investigated projection-augmented paper prints [16, 18, 34], even in large poster sizes [36]. Work on interactive paper origami proposes manually attached LEDs as active output on folded paper objects [24]. Prototypes from previous work use projection, tiled rigid displays or rectangular flexible displays on plastic substrates. The PrintScreen plat-

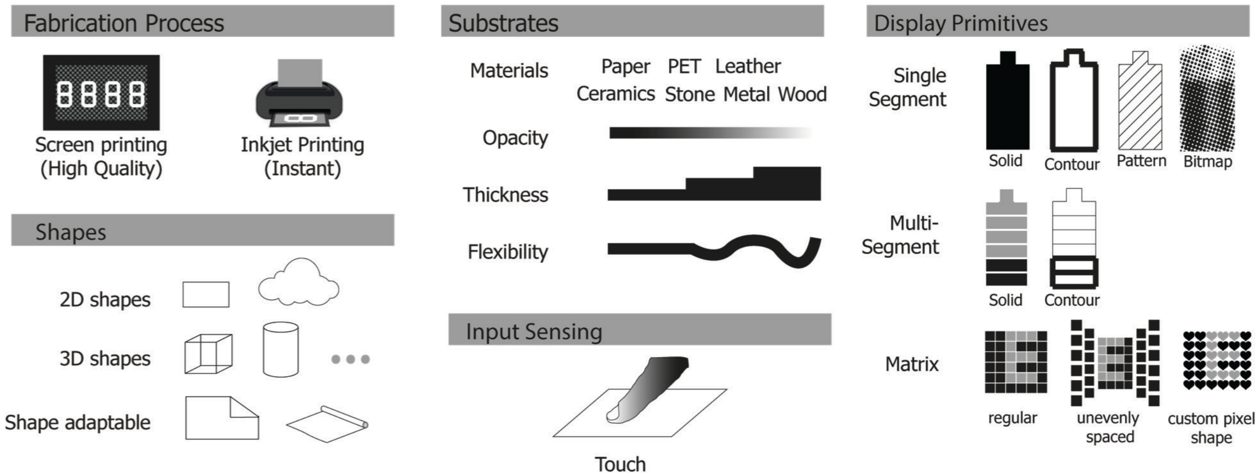

Figure 2. Five-dimensional design space for digital fabrication of customized displays.

form opens up substantially more degrees of freedom in designing custom displays for HCI prototypes.

DESIGN SPACE OF CUSTOMIZED DISPLAYS

Custom-made displays open up considerably more degrees of freedom for the design than off-the-shelf displays. We identified five key dimensions for digital fabrication of customized displays, which systematize the design options. This section provides an overview of these dimensions, which form the foundation of the PrintScreen platform. The design space is illustrated in Fig. 2.

Fabrication Process: How to print

We propose a digital fabrication approach for production of customized displays. The designer generates a digital model of the display and then prints this model. Ideally, printing is as instant and easy as sending a document to an office printer. This would enable prototyping with rapid and many design iterations. We introduce an instant fabrication process based on conductive inkjet printing, which comes close to this ease of fabrication. Moreover, we propose a second fabrication approach, which requires screen-printing on a beginner's level. While it takes longer to fabricate a display, it is of higher quality and supports the full set of substrate materials, display primitives and sensing modes presented in this paper.

Substrate Materials: On what to print

Customized displays may be printed on various materials that vary in thickness, flexibility, texture and opacity. PrintScreen supports many substrate materials, including highly deformable and foldable office paper, transparent or nontransparent PET film, leather, wood, ceramics, stone (marble) and metal (steel). The display adds only 110 µm of thickness to the base substrate.

Display Primitives: What to print

Customized displays offer a large variety of design options regarding the display contents, far more than the regular matrix which one would intuitively think of. If contents are known at design time, segmented and multi-segmented displays are a compelling option. They feature very sharp contours and homogeneous fill, even if printed in large sizes, while nevertheless being easy to control. In addition, we introduce segments that feature an arbitrary bitmap pattern which is defined at design-time. For very dynamic applications, matrix displays are the preferred option. PrintScreen allows for printing conventional matrices in a custom resolution, but adds options for customization by offering unevenly spaced matrices and pixels in custom shapes.

Display Shapes: What form factors are possible

A key question for any application is the size and shape of the display. With off-the-shelf displays, the designer has relatively little choice. Non-rectangular outlines, extreme aspect ratios, curved or 3D shapes are typically not available. However, such non-standard shapes are important to make an embedded display fit within an object or the physical environment. PrintScreen offers the designer a much higher degree of design flexibility. It supports custom 2D outlines; moreover it enables custom 3D shapes, which are created by bending and folding. Moreover, displays can be made shape-adaptable and resizable, using bending, folding or rolling, but are not stretchable.

Integrated Input Sensing: How to interact

User input is a key property of interactive display surfaces. We contribute a generic platform for sensing of user input, which is directly integrated with the printed display. As examples we demonstrate touch input.

In the following main part of the paper, we will discuss each of these dimensions.

FABRICATION PROCESS

We contribute two approaches to allow non-experts to fabricate customized thin-film electroluminescent displays: a high-quality and an instant process. Both are easy to learn and perform for non-experts and require only off-the-shelf tools and consumables.

Printed Electroluminescent Displays

Thin-film electroluminescent displays actively emit light. A segment of a TFEL display consists of two overlaid electrodes, which act as a capacitor. Inside the capacitor is a

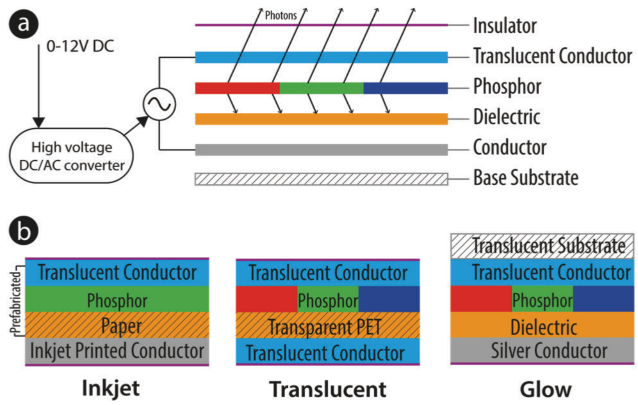

Figure 3. a) Composition of the printed layers of an electroluminescent display: Silver Conductor (C2131014D3, 100mΩ/sq), a barium titanate based dielectric (D2070209P6), phosphor (e.g. C2101125P4) and a PEDOT based translucent conductor (D2070209P6, 500-700 Ω/sq). b) Variations of the standard structure to create translucent displays, display glowing through materials or inkjet-printable displays.

layer made of phosphor and a dielectric layer. If a high voltage, low current AC signal is applied, the phosphor emits photons (see Fig. 3 a). TFEL displays are used in many commercial products, e.g., as backlight for car dashboards.

Digital Design

The designer of the display first creates a digital design in a standard 2D vector graphics editor, such as Adobe Illustrator. Each segment or pixel is created as if it was ordinary visual artwork, using the application's tools for creating lines, polygons, text, fills, etc. Hence, designing an interactive display is pretty much comparable to designing conventional 2D graphics.

For screen printing, the designer generates four adjacent identical copies of the design – one for each print layer (see Fig 3). If segments and pixels shall be printed in more than one color, one more layer is added for each additional color. Laying out the copies adjacently allows to create one single print mask that contains all print layers, making screen printing cheaper and faster. For inkjet printing, only one copy is required. Next, the designer lays out the wires that are required for controlling the segments. The minimum width is 300 µm. On the first copy (bottom electrode), each segment is connected with an individual input pin. For screen printing, all segments on the fourth copy (top electrode) are connected to a shared ground pin. Alternatively a grid of segments or pixels can be wired as a matrix.

Screen Printing for High Quality

For screen printing, we used off-the-shelf equipment for hobbyists (approx. 200 €). We follow a standard multi-layer screen-printing process [22], which is commonly used for printing on paper or on fabrics and can be easily learned by non-experts. Each layer of the display stack is printed successively, from bottom to top. Details on the inks, available

Figure 4. Dual sided print on office paper

colors, mesh density of the screen and the instructions of use can be found in [8]. For multi-color displays, two or more layers of differently-colored phosphor are printed. Finally, the top layer is insulated with acrylic insulating spray (dielectric strength 80kV/mm). Overall, the display adds 110 µm to the substrate. We successfully printed a display on a 10 µm thick PET film (Gwent, F2111117D1), resulting in 120 µm as the minimal thickness of the final printed display. To create a dual-sided display (see Fig. 4), the same process can be repeated on the reverse side of the substrate.

Segments can be printed in a resolution of up to 30 lines per inch (lpi). As a rule of thumb, this corresponds approximately to 60 pixels per inch (ppi). For comparison, a conventional office laser printer has between 35 ppi (300 dpi) and 75 ppi (600 dpi). We use printed guidelines to improve inter-layer alignment. However, the manual printing process introduces an offset between individual layers. We analyzed 10 display samples and measured the maximum offset between individual layers. We found the designer can ensure the full segment be functional by enlarging the top and bottom electrodes as well as the dielectric by 300 µm to each side.

Printing of the application examples presented in this paper took one person between two and four hours. The time depends not on the complexity of the display contents, but on the display size and the number of different colors. The cost

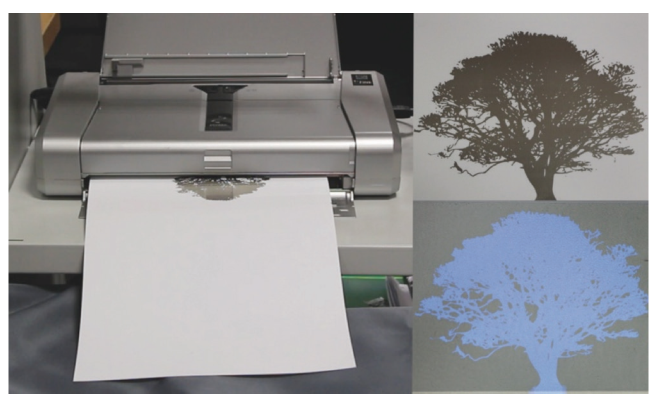

Figure 5. Instant inkjet printing. A printed electrode (left, upper right) is illuminated (lower right).

of consumables for printing a completely covered A4-sized display is approx. 2 € for the screen mesh and 19 € for the inks. Many applications require segments only on some locations on the substrate, which can further reduce cost quite considerably.

Conductive Inkjet Printing for Instant Fabrication

The second fabrication process ensures instant fabrication, which is important for design iterations in rapid prototyping. No screen print equipment is required. However, it offers fewer design options.

The designer uses a prefabricated display film (Fig. 3b and Fig. 5). This film contains all printed layers except the bottom electrode. It consists of a sheet of coated paper (Mitsubishi NB-WF-3GF100), which acts as substrate and dielectric. On top of it, a fully filled layer of phosphor (in one color) and a fully filled layer of transparent conductor is printed. This film can be fabricated in bulk using screen printing, as describe above; in the future a paper manufacturer could make it commercially available for purchase.

The designer uses conductive inkjet printing [14] to print the digital design (aka. the bottom electrode layer) on the reverse side of the prefabricated display film. We use an off-the-shelf, consumer-grade inkjet printer (Canon IP-100) with Mitsubishi NBSIJ-MU10 silver ink. Finally, to seal the bottom electrodes, insulating spray is applied, or a thin layer of dielectric (e.g. office paper) is glued or laminated onto the reverse side of the display.

In the prefabricated film, the top electrode, phosphor and dielectric cover the entire surface. This restricts what types of display can be realized. In particular, the display is unicolored. Only segments, but no matrix can be designed. Segments always have a solid fill, and wires used for tethering the electrodes with the controller light up on the display. Touch sensing is restricted to a single touch contact on the entire display. However, contours and surface patterns can have a high resolution, which is defined by the resolution of the inkjet printer (600 dpi).

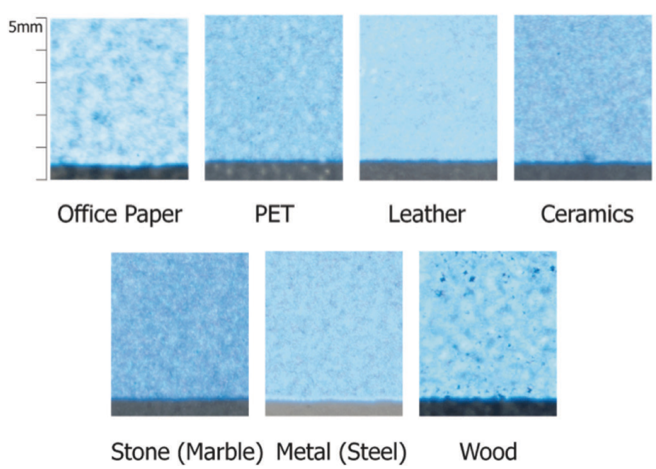

Figure 6. Enlarged view of an illuminated segment and its contour, printed on various substrates.

Controller

To light up a display segment, the controller applies a high-voltage, low current AC signal between the upper and lower electrodes. The luminance of a display segment or pixel is controlled using pulse-width modulation, a standard method for controlling the luminance of LEDs.

For mobile applications, our prototypical controller uses a small driver IC (Model Durel D356B, sine wave, 220 Vpp, 230Hz to 390Hz). This driver IC generates the high-voltage AC signal from a 1.0-7.0V DC power source. If a higher luminance is required, a stronger 0-12.0V driver IC with a slightly bigger footprint can be used (Model Sparkfun DC12V10M, sine wave, 220Vpp, 800Hz to 3.5KHz). A microcontroller (ATmega2560) triggers optocouplers (MOC3063) for multiplexing the high-voltage signal between display pins.

The TFEL-specific ghosting effect in passive matrix displays can be significantly reduced by using a slightly modified controller design [11], thus further increasing the contrast of the matrix. To interface the display with the controller, we solder copper wires onto printed pin areas. For a larger number of pins, a flat-ribbon cable and 3M Electrically Conductive Adhesive Transfer Tape 9703 can be used.

The number of output pins of the internal microcontroller restricts our controller to up to 40 separate segments or a 20x20 matrix with passive matrix time-division multiplexing. However, the number of segments or pixels can be substantially increased by using multiplexers to increase the number of output pins of the microcontroller and additional optocouplers to switch high voltages. To keep the size of the controller (currently 5x7cm) small, small optocouplers (TLP266J) can be used.

Despite high voltages, the approach is safe and energy efficient, and even usable for fully mobile applications, because the current is very low and the TFEL display is very energy efficient (2.6 mW/cm^2 in highest luminance, using DC12V10M). The inkjet method uses a thicker dielectric; therefore power consumption increases to 38 mW/cm^2.

SUBSTRATE MATERIALS

For applications in ubiquitous, embedded and wearable interaction, it is of high importance that the display can be integrated with a variety of materials. Our screen printing approach allows for printing the display right onto the substrate material, integrating it fully with the object and making additional carrier materials and lamination obsolete.

We successfully printed displays on a wide variety of materials, including highly flexible, translucent and transparent materials (see. Fig. 6). Among them was office paper, PET, leather, ceramics, marble, steel and untreated wood. Figure 6 shows that the surface structure, contours and color saturation of an illuminated display segment varies depending on the material; the contours of the printed segment are more or less crisp.

We experienced that successful prints largely depend on the (ideally high) smoothness of the material's surface, leading to a homogenous display surface and crisp contours. We could not print on extremely uneven surfaces, such as cotton fabrics or suede leather. But we could successfully print on quite porous materials, such as office paper and untreated wood, with some decrease in homogeneity and crisp contours. In our experience the absorbency of the material is not decisive: we could print even on steel and stone in a very high quality.

Since the phosphor inks are not transparent, printing on the material inherently changes its visual properties. To fully hide the display components, the display can be printed on the reverse side of translucent materials. We also successfully printed the display on the backside of translucent materials, such as PET (see Fig. 8), paper (see Fig. 9), and wood veneer (see Fig. 6 lower right).

DISPLAY PRIMITIVES

Custom displays come in a large variety, ranging from easy to control segmented displays to highly generic matrix displays. In this section, we contribute a systematic overview of display primitives, structuring known primitives and contributing new ones. This acts as a graphical inventory from which the designer can combine elements to design the visual contents of the display. As PrintScreen applies principles from 2D vector graphics for the digital fabrication approach, the designer has extensive design flexibility and can make use of the powerful tools of modern vector graphics editors.

Single Segment

A single segment features an area or a contour, or a combination of both. A TFEL display homogeneously lights up the element, even over a large surface area. A segment features sharp contours, even if printed in large size. A segment can be printed with a high resolution of 60 ppi with screen print and 75 ppi with conductive inkjet print.

We contribute over previous work on display segments by allowing the designer to very flexibly vary the shape, the fill and the contour of the segment in the digital design. This is illustrated in Figure 7. The fill can be either *empty* (not lighting, fully transparent), *solid* (lighting homogeneously in one color), can contain *line art or line patterns* as a visible structure, or can show a predefined greyscale *bitmap image*. For bitmap images, we use half-toning, a method that produces greyscale with one color by printing dots of different density and size on the substrate.

A non-solid fill is realized as follows: like for a solid fill, the top and bottom electrodes and the dielectric are kept solid, covering the entire area of the segment. In contrast, phosphor is printed only at locations that should light up, i.e. lines for line patterns or dots for half-toning. In our experience modifying the phosphor layer is preferable to modifying one of the electrode layers, as the former approach ensures that the full electrode remains conductive, independently of the pattern.

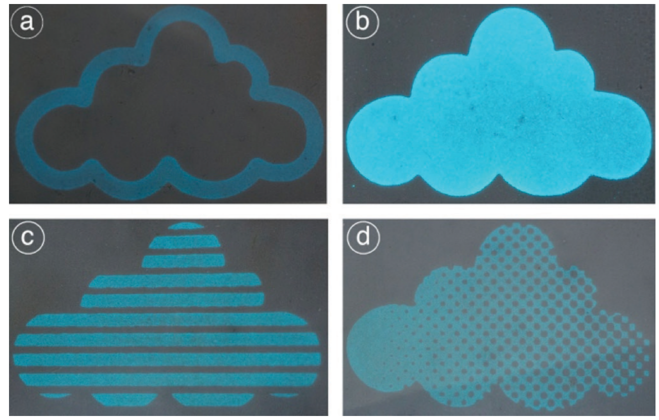

Figure 7. Display segments: (a) contour, (b) solid fill, (c) line pattern fill, (d) bitmap fill.

The contour of a segment can be solid or made of a dashed pattern. If realized as two separate electrodes, contour and filled area can be separately controlled. Displayed dots should have a minimum diameter of 300 microns.

Multi-Segment

A multi-segment splits a single segment up into several sub-segments that can be independently controlled. Examples include a seven-segment display for numerical values or a progress bar. The principles introduced for single segments fully apply to multi-segments.

Matrix

PrintScreen supports printing a regular matrix display (Fig. 8a). We print the rows of the matrix as the bottom electrode and the columns of the matrix as the top electrodes. The phosphor layer and dielectric are continuous. Time-multiplexing between rows and columns allows for addressing individual pixels. The designer can define the size of the matrix and the pixel density. The maximum density is defined by the resolution of the screen printing equipment,

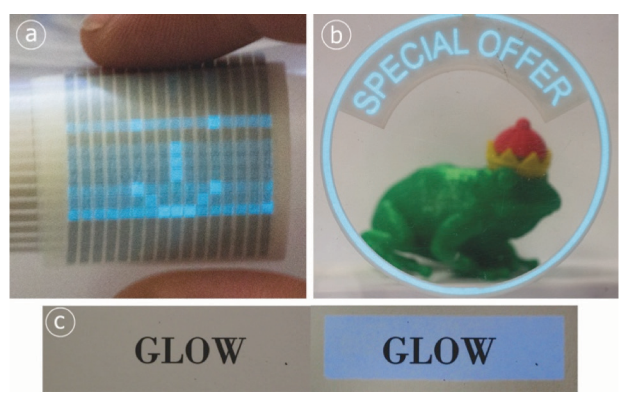

Figure 8. a) Passive Matrix Display. b) Translucent displayed on transparent PET film, in front of an object. c) Integration with laser-printed static visuals.

in our case 30 parallel lines per inch, leading to 30 pixels per inch.

We extend the design possibilities for matrix displays in two ways: (1) *Unevenly-spaced and -sized pixels* allow for varying the information density, e.g. higher resolution in the center and lower resolution in the periphery of a display. (2) *Custom-shaped pixels* allow for creating a unique visual appearance of the display, e.g. for digital signage or artistic installations. Both these options come at virtually no extra cost, as it is very easy to modify these parameters in the digital design.

Translucent Display Segments

To fabricate translucent display segments, the back electrode is printed with translucent conductive ink on the reverse side of a transparent PET film (see Fig. 3b). The film itself acts as the dielectric, eliminating the need for non-transparent dielectric ink. The phosphor and top electrode layers are printed on the front side. The conductor and phosphor inks are translucent, leading to a translucency of 32% at positions where segments are printed. Note that the display is fully transparent at locations without segments. Fig. 8b shows an application example for a shop window showcase.

Integration with Static Visual Print

A display can be printed alongside and integrated with static visual print. The designer uses an office laser or inkjet printer to print static visuals onto the paper or PET substrate. Next, display primitives are printed with screen printing onto the same substrate. This enables the following functionality:

Adjacent: Display primitives can be adjacent to printed visuals, for instance allowing for underlines or pop-out elements that light up on demand.

Contour: They can be more directly integrated. For instance, a static printed headline can be augmented by a luminescent contour. As long as the segment is not filled, visual print inside the segment remains fully visible.

Highlight: If the display primitive is printed at the reverse side of a slightly translucent substrate (see Fig. 3b), it can glow though static print on the front side and act as a dynamic highlight. The example in Fig. 8c demonstrates a highlight printed on the reverse side of office paper.

Integration with Printed Electronics

PrintScreen enables integrating display primitives with additional printed electronic applications on a single substrate. The bottom electrode layer can be used for designing additional electronics next to display primitives. Using silver ink for the bottom electrode, users can design printed traces and components. The principles for silver-ink printed components from previous work directly transfer to this case, e.g. for printing sensors [7, 9, 13]. Moreover, additional surface-mount components can be soldered onto the substrate.

DISPLAY SHAPES

PrintScreen offers the designer a high degree of design flexibility, supporting custom 2D and 3D shapes as well as reshapeable displays.

2D Shapes

Virtually any (rectangular, circular, irregular) 2D contour of the display can be realized in the digital design and then cut out of the fabricated display substrate. The only restriction is that each segment must be connected with the controller. The size of a display can range from only a few square centimeters up to large sizes. Screen printing of up to A2 size is feasible with hobbyist's toolkits.

3D Shapes

Screen printing does not allow for printing on curved objects. However, it supports printing on flexible substrates. Once printed the substrate can be deformed to create curved or folded 3D surfaces (see the examples in Fig. 1 and Fig. 10.

Shape adaptable

The flexibility of the substrate even allows for resizable and deformable displays. In technical experiments, we could demonstrate that the printed display can be folded anywhere on its surface and remains fully functional. It can also be rolled up on a scroll with a radius of 3 mm; this enables for applications for rollout displays. A technical evaluation shows that the displays are very robust to repeated bending or folding.

INTEGRATED SENSING OF USER INPUT

Sensing of user input is a key requirement for interactive display surfaces. We contribute an approach for integrating different modalities of input sensing with a printed TFEL display, using the same set of electrodes both for display and for sensing. It is *not* necessary to print additional sensing elements on top or behind the display, as it would be necessary for LCD screens. We demonstrate the principle with capacitive touch sensing.

The approach is based on the key insight that the phosphor layer only lights up when a high AC voltage is applied on one electrode while the electrode on the other layer is grounded. It does not light up when DC or a low voltage AC (we identified < 14 V) is applied, or when one electrode is set to high impedance. Many sensing approaches fulfill these requirements, e.g. for sensing of touch [6, 7, 26], hover [7] or deformation [7], to give only a few examples.

By time-multiplexing between a display and a sensing cycle, the electrodes on one, or even on both layers, can be used for sensing. In case of DC sensing, the driver IC is turned off during the sensing cycle. The time for discharging depends on the charge of the internal capacitors. In our implementation, we measured a maximum discharging time of 1.7ms.

As an example instantiation, we implemented capacitive touch sensing using projected capacitance [26]. During the sensing cycle, we leave the high voltage AC signal on the lower electrode, set the higher electrode to high impedance and measure the transmitted signal. When touching the electrode, the signal amplitude drops (see Fig. 9). The amplitude of the signal is used for recognizing touch contact, as introduced in [26].

If display and sensing cycles alternate quickly and the display cycle is sufficiently long, there is no perceivable decrease in display quality. We identified the following cycle durations to not add flickering: a display cycle of 5ms is followed by a sensing cycle of 2ms. This results in a frame rate of 140 Hz. The sensing cycle decreases the luminance of the display by 24%, which however can be fully compensated for by increasing the AC voltage. If used in a passive matrix display, the frame rate is divided by the number of lines of the display.

The spatial resolution of sensing depends on the number, size and arrangement of display electrodes. If required, additional electrodes used exclusively for purposes of sensing can be printed in-between display segments. It is also possible to enlarge the top and lower electrodes of a display segment for sensing, without increasing the segment on the phosphor layer.

APPLICATION EXAMPLES

We present five application examples of custom-printed displays. They instantiate various dimensions of the design space and demonstrate the potential for applications in ubiquitous, mobile and wearable computing. The applications are illustrated in Fig. 10

Interactive Paper Postcard

Interactive display segments can be integrated with static visual print. We printed a paper postcard that features on-demand visual information on a historical car. Two printed touch areas capture user input. The display segments are printed on the reverse side of the postcard. This application shows the high resolution of very custom-shaped segments and demonstrates the applicability for augmented paper and smart signage applications.

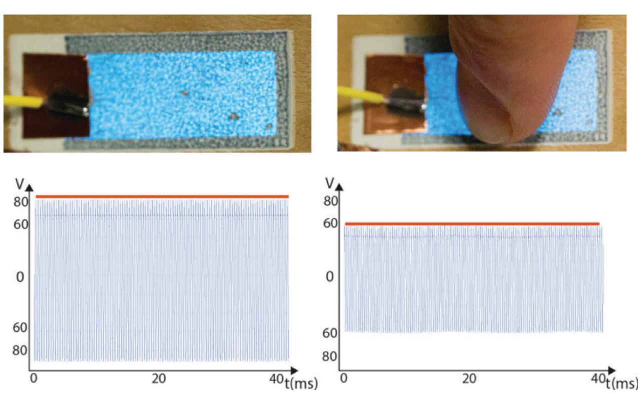

Figure 9. Touch sensing. The amplitude of the AC signal drops when the segment is touched.

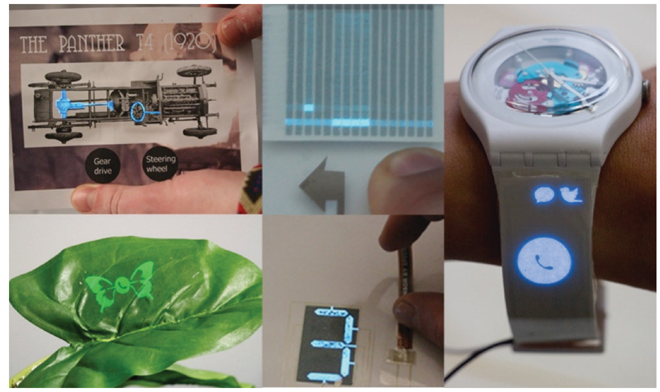

Figure 10. Application examples

Interactive Watchstrap

PrintScreen enables customized wearable displays. In this application, a notification display is integrated in a watchstrap of a traditional wristwatch. It is printed on the backside of a thin white PET film, which is laminated onto the watchstrap. The display can be customized to fit the individual shape of the watchstrap. This smartwatch concept has the benefit to maintain the esthetics of a traditional watch.

Printed Pong

To demonstrate interaction with a printed matrix display and its responsiveness, we implemented an instantiation of the Pong game. The 16x16 matrix display features two capacitive touch buttons to control the paddle. Technical Evaluation.

Awareness Flower

We augmented an artificial plant with displays on the backside of its flexible leafs, to provide awareness information. If an update (e.g. a new e-mail) arrives, the segment lights up. This application demonstrates how PrintScreen enables ubiquitous displays that seamlessly integrate with the underlying object and fade into the background when not needed.

Integration with Electronics

This application demonstrates that PrintScreen can be used for creating flexible circuit boards with integrated display elements. The bottom electrode layer contains additional printed circuitry for wiring of additional electronic components. A physical bend sensor allows the user to modify the number on a seven-segment display.

TECHNICAL EVALUATION

Luminance

The light intensity of the display can be controlled by varying the AC voltage (amplitude and frequency). We analyzed the maximum light intensity of the displays. It depends on several factors: the substrate, the AC voltage and the strength of the inverter. When driven with the DC12V10M inverter at its maximum input voltage of 12V DC, the luminance of the display varies between 120 and 280 cd/m^2. On paper, PET, ceramics and leather, we measured a maximum luminance of approx. 170 cd/m^2. On very smooth materials (steel and marble), 280 and 250 cd/m^2 are reached. On wood, a quite porous material, we measured only 120 cd/m^2. In our experience, the strength of the inverter is the main limiting factor. In experiments with a stronger inverter, we measured intensities between 270 and 570 cd/m^2 at 18V DC. When using the mobile driver IC chip [28] with 7V DC, the displays are less bright, ranging between 15 and 35 cd/m^2. This is comparable to a super bright white LED.

Bending and Folding

To analyze how robust the display is when repeatedly bent or folded, we used an automated test setup. We used a display sample with a 6x1.5cm single segment, printed on office paper. A simple robotic apparatus bent or folded the display repeatedly, returning each time to a completely flattened state. A light sensor, placed 10 cm above the display surface when in flat state, automatically measured the luminosity after each deformation.

In a first test, the apparatus bent the display successively 10,000 times to a radius of 1.5 cm. After the test, the display was still functional and did not show any decrease in luminance. We tested this high number of repetitions to account for continuous deformations occurring when the display is used in wearable applications.

In a second test, the apparatus fully folded (with a sharp folding crease) and unfolded a different display sample a total of 3,411 times before parts of the segment ceased to emit light. During the test, the display did not show any decrease in luminance.

DISCUSSION AND LIMITATIONS

Ease of Fabrication

All display samples presented in this paper were printed by two persons who both were not familiar with screen printing before joining this project. They used online tutorials and videos on the Web to learn the process. It took them between 3 to 5 hours to get familiar with the theory and another day to get practical experience. They did not encounter any real difficulties. One of the persons first had problems with homogeneously applying the UV-sensitive emulsion onto the mesh for UV lithography, but had learned doing it correctly after a few trials. Fine prints with thin lines require a steady hand. Despite the imprecision of the manual process, our non-experts could robustly print conductive lines and lighting dots of 300 μm width and diameter. Printing of the displays for our example applications took between 2 and 4 hours. This demonstrates the practical feasibility of the approach.

Display Color

Our process requires for each segment or pixel to choose the color at design time. For our display samples, we used only one color. A full color display could be realized by printing three red, green and blue sub-pixels for each pixel [15]. Given the maximum pixel density in manual print, this is a viable approach only for displays that are looked at from some distance.

Safety

All substances used for fabrication of the displays are non-toxic.

Safety for production: Users should read the health and safety guidelines in the material data sheets of the inks. It is recommended that the printing process take place in a well-aired room especially when curing the inks. Users should wear rubber gloves and goggles to protect eyes and hands. The display should be sealed properly.

Safety after production: After the inks are cured, the display is safe to interact with. A current of max. 10mA is considered being physiologically safe [31]. For example, the EL driver IC can provide a maximum output current of 1.0 mA at 220 Vpp [28]. This driver IC can drive a segment area of 4 sq. inches. If we assume 10 driver ICs are connected in a parallel circuit (driving a surface of 40 sq. inch, a reasonable size for most mobile/wearable applications) the overall current is max. 10mA.. If stronger inverters are used or if the display is exposed to mechanical stress or scratching, we recommend lamination with an insulating film.

Comparison with OLED Displays and Electronic Paper

In applications where a high-resolution matrix display or use of a full-color display is a prime requirement, off-the-shelf OLED or electrophoretic displays are still the solution of choice. However, if very strong bendability or even foldability is required for functional interface prototypes, our approach is without competitors, as to our knowledge such displays are neither commercially available nor can they be produced using a different approach. Likewise, PrintScreen is to our knowledge the only solution for designers, makers and HCI experts that allows direct integration of displays with various base substrates, very thin dual-sided and translucent displays and custom shapes.

CONCLUSION

PrintScreen is an enabling technology for digital fabrication of customized thin-film displays. We presented a systematic overview of graphical display primitives that act as buildings blocks for the digital design of the display. In order to instantiate the design, PrintScreen contributes two methods for rapid and inexpensive fabrication of the display, in a lab environment, print shop or even at home. The displays are deformable (even fully foldable and rollable) and can be highly customized by the user in several dimensions: their 2D and 3D shape, the material they are printed on, and the way contents are displayed. We further presented a framework that integrates sensing of user input (e.g., touch input) right into the display. Due to its versatility, PrintScreen opens up a wide space of new applications in ubiquitous, mobile and wearable computing.

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