Displays as a Material: A Route to Making Displays More Pervasive

David Sweeney, Nicholas Chen, Steve Hodges, and Tobias Grosse-Puppendahl, *Microsoft Research*

The plummeting cost of TVs and computer monitors, widespread adoption of mobile devices, and advent of wearable devices means that there are now more digital displays than ever before. But these are still outnumbered by the vast array of nondigital displays in the world in the form of text and graphics permanently printed on various objects around us. Turning these static surfaces into dynamic displays offers several benefits, including improved awareness of and faster access to relevant information;[1] more freedom in terms of display locations, which would improve ergonomics and aesthetics; and the potential for new, more personalized products with ever-changing designs that can seamlessly blend into the surroundings.

Today's displays are typically thought of as discrete components or modules around which devices are constructed. For digital displays to become more pervasive, they need to have the properties of materials like textiles and plastic film and other construction materials. Such an approach unlocks many scenarios currently restricted to static, printed displays. For example, a digital display material that can be cut and stretched could be applied to or built into arbitrarily shaped objects and could scale from a device- to building-size display.[2,3]

In our research, we're working to realize this kind of display material. Fundamental to our approach is a move away from the row-column addressing architecture that dominates traditional displays. More specifically, we propose an architecture that relies on *autonomous pixels*—that is, pixels that independently sense input and convert it to a corresponding visual output. Two different prototypes reveal the challenges and potential of autonomous pixels, highlighting how digital displays supplied as a flexible material can help foster the development of new applications.

A seamless high-resolution display for large-scale applications, such as billboards, is all but impossible with a grid topology.

LIMITATIONS OF THE GRID

A major barrier that has limited the versatility of contemporary displays comes from the hegemony of the grid-based topology used in their construction. This architecture, in which pixels lie at the intersection of a row wire and a column wire, provides a straightforward and convenient means for addressing each pixel. The grid topology is ideal for creating displays with rectangular shapes, because wires can simply extend across the full area of the display. But nonrectangular displays are difficult and therefore more costly to manufacture, because they need exotic wire-routing schemes, and, even then, the shapes they can take are extremely constrained.

Realizing a nonflat matrix display presents an even greater challenge. The fragility of the fine row and column wires in a grid-based display—where a single break can cause numerous pixels to stop working—means that these displays rarely support bending, compression, or stretching. But if these limitations could be overcome, it would unlock many new applications for pervasive digital displays.

Another limitation that arises from the grid topology is scalability. Increasing the size of a single display is only feasible within limits; ultimately, the number and density of wires becomes unworkable with a very large display. The alternative is to tile smaller displays, but modern active matrix display panels have an inherent bezel that precludes seamless tiling. The bezel is necessary because the row and column wires are connected to dedicated driver chips mounted along the outside edges of the panel. These chips are usually made using silicon, further introducing constraints on flexibility and fragility. As such, a seamless high-resolution display for large-scale applications, such as billboards and buildings, is all but impossible with a grid topology.

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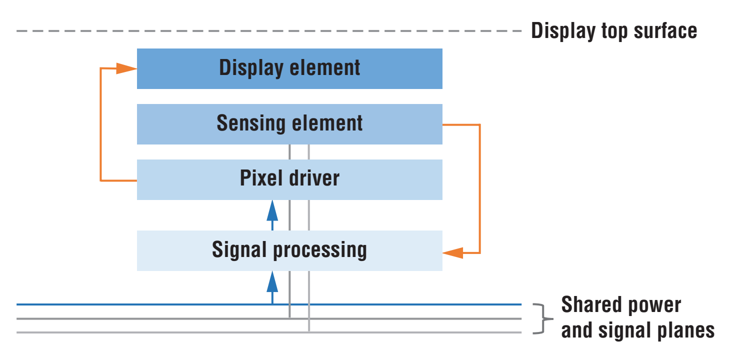

Figure 1. An autonomous pixel incorporates a sensing element that directly controls the pixel's visible contents. This shows the structure of our second prototype, where the photo sensor is directly behind the display media and faces up through it.

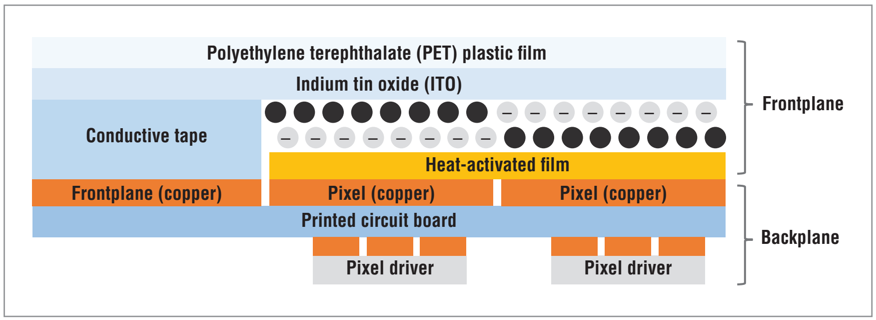

Figure 2. The stack-up in our prototype displays comprises multiple layers that are laminated together.

DISPLAYS USING AUTONOMOUS PIXELS

Departing from the grid opens up opportunities for more flexible, versatile, and robust displays. In previous work, Angie Chandler and her colleagues demonstrated that it was possible to use serially connected display elements to create displays with a wide variety of shapes.[4] We use a different approach to create the same versatility.

In our architecture, the pixels are independently responsible for sensing a signal, processing that signal, and using this information to control the display. In this autonomous pixel scheme, the only electrical connections to pixels are via conductive planes, which deliver power and one or two global signals shared across all pixels (see Figure 1). By incorporating sensing and signal processing capabilities into each pixel site, this architecture opens up new ways to address pixels and transfer data, freeing the display from the confines of the row-column grid.

The autonomous pixel architecture offers several benefits over a display built using a row-column matrix. Chief among these is that the display uses conductive planes instead of a delicate grid of wires: without dedicated signals running to each pixel, it becomes possible to cut out or shape parts of the display to support a variety of nonplanar applications. Also, autonomous pixel displays remove the constraint that pixels must be arranged in a rectangular grid; they can have differing shapes, arbitrary positions, and varying density. Finally, because the operating circuitry is local to each pixel, there's no need to interface with external driving electronics, making the displays seamlessly scalable.

Developing Prototype Displays

The detailed construction of a display depends on the underlying display technology, but most displays are based on a stack-up of different materials, which are laminated on top of each other. At a coarse granularity, there are two major layers—the frontplane forms the image from an optical perspective, while the backplane contains the electronics necessary to control the frontplane. The high-resolution, high-framerate, defect-free displays used for consumer devices, such as smartphones and TVs, are manufactured on sophisticated and expensive production lines. But if you're prepared to compromise on display quality, it can be remarkably straightforward to prototype custom displays in a lab environment.

The prototype displays we describe here are based on an electrophoretic display (EPD) frontplane—the same kind of technology used in e-readers like the Amazon Kindle.[5] This material is supplied in sheet form with the EPD media itself laminated onto a polyethylene terephthalate (PET) plastic film.[6] There is a transparent layer of conductive indium tin oxide (ITO) on the PET film, which is in contact with one side of the e-paper media, whereas the other side of the media is supplied coated in a layer of heat-activated film. This layer stack-up is shown in Figure 2.

The EPD media is a layer of tiny black and white spheres. The white spheres carry an electric charge, which means that by generating a suitable electric field, they can be moved toward or away from the display surface, thereby making the image more white or black, respectively. Such a field is created by applying a voltage

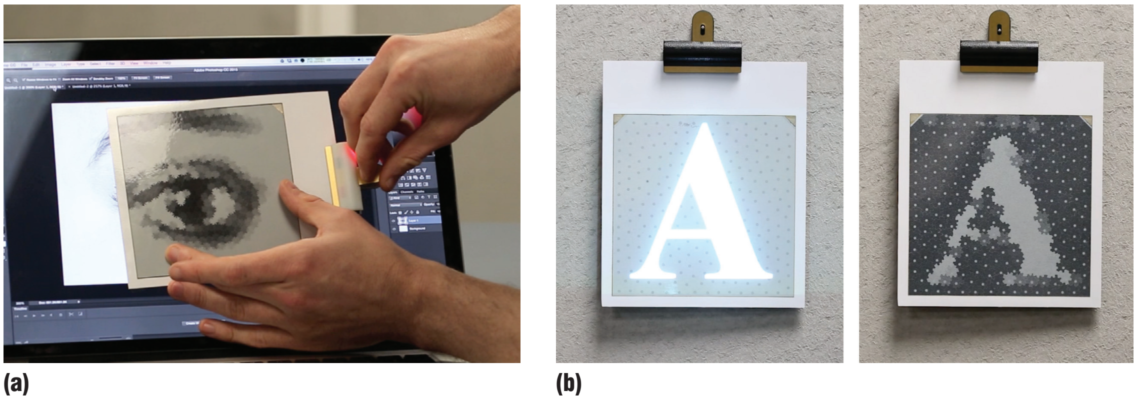

Figure 3. Two macroscale, prototype displays demonstrating the viability of the autonomous pixel architecture. (a) Our first prototype comprises around 600 autonomous pixels with light-sensitive elements facing toward the rear. The display can sense an image on a computer screen behind and take a copy—a bit like photocopying without a copier. (b) Our second prototype features approximately 300 pixels with light-sensitive elements that face through the display surface, enabling an image projected onto the surface to be captured.

between the transparent ITO layer at the front of the display and the substrate to which the display is laminated. The field is controlled on a per-pixel basis.

The two macroscale prototype displays we developed demonstrate the viability of the autonomous pixel architecture using EPD material as the frontplane media. Each pixel combines a photodiode light sensor with EPD driving the circuitry in the backplane. The backplane substrate is a very thin printed circuit board, resulting in a flexible display that looks a bit like a large Polaroid print.

Our first prototype is the simpler of the two. It has the photodiodes behind the display, allowing the display to capture imagery from an emissive screen (see Figure 3a). In the second prototype, the photodiodes face forward, looking though the EPD material and sensing the intensity of light incident on the display (Figure 3b). This enables the display to be controlled by projecting light onto it. (For more detailed information about how we built our prototypes, see the "Step-by-Step Guide: Building a Display in the Lab" sidebar.)

Prototype Operation

The display senses light intensity at each pixel position using a photodiode. In the simpler of our two prototypes, if the intensity is above a certain threshold, the driving circuitry is activated, which causes the EPD media to change color. In our more advanced prototype, we add global "gain" and "threshold" signals. These two additional signals feed into the signal conditioning circuitry within each pixel and specify sensitivity and switching threshold. Erasing the display is accomplished by reversing the polarity of the power planes.

The design choices we made in our current prototypes aimed to keep implementation particularly simple. The bi-stable properties of the EPD media maintain state, bypassing the need to include memory elements at each pixel. The use of light conveniently allows us to leverage off-the-shelf displays and projectors to control the display. However, we imagine that with more engineering resources, our autonomous pixel architecture could be extended in a variety of ways.

In the current prototypes, the incoming photocurrent is directly mapped to the display using purely analog signal conditioning, which reduces the necessary circuitry. But it would be possible to integrate more advanced functionality within each pixel. For example, digital decoding circuitry in each pixel could be used to sense data modulated onto the incident light. This would provide a mechanism to change pixel sensitivity, erase pixel content, or control pixels with finer granularity. Our prototypes require a small amount of power in order to sense and render a new image, and this is supplied by a battery built into a "bulldog clip" that attaches to contacts on one edge of the display (see Figure 3b). However, we intend to provide power from behind the display in future iterations, allowing seamless tiling of displays. Ultimately, we'd like to leverage energy-harvesting techniques along the lines of the work done by Artem Dementyev and his colleagues.[7]

It's also important to note that autonomous pixel displays aren't limited to EPDs. We believe our architecture will generalize to a range of input and output modalities; for example, the addition of memory elements and

STEP-BY-STEP GUIDE: BUILDING A DISPLAY IN THE LAB

It can be remarkably straightforward to build a prototype display using regular lab equipment. In our case, the display backplane is a regular printed circuit board (PCB), as shown in Figure A1. The position, size, and shape of each pixel is defined by a series of electrodes running across the top surface of the PCB (see Figure A2). The electrophoretic display (EPD) media is supplied in sheet form and must be cut to match the overall size of the display (see Figure A3). We use ComFlec film from OED Technologies (www.oedtech.com).

Before applying the EPD film frontplane to the PCB backplane, it is necessary to prepare a connection to the indium tin oxide (ITO) layer on the front of the display. First the aluminum release sheet is removed from a corner (or edge) of the media to reveal the EPD material itself (see Figure B1). Then, the EPD material can be removed at that location; the exposed ITO is cleaned using isopropyl alcohol (see Figure B2). A small piece of double-sided self-adhesive tape is placed on the frontplane-driving segment (see Figure B3). We use electrically conductive tape type 9703 from 3M, but a variety of products are suitable, both anisotropic "Z" tape and regular electrically conductive adhesive tape. Alternatively, conductive epoxy such as CircuitWorks CW2400 can make a more robust connection, but it's harder to apply. When the conductive tape is in place, the remaining aluminum release sheet is removed (see Figure B4).

Finally, the frontplane and the PCB backplane are sandwiched together and bonded (see Figure C) by activating the heat-activated-film adhesive (which was applied to the media by the supplier). We do this using a regular T-shirt press at 110 °C. To make the display more robust and improve appearance, we apply a white vinyl bezel which we cut to size on a regular vinyl cutter. The finished product is shown in Figure 3 in the main text.

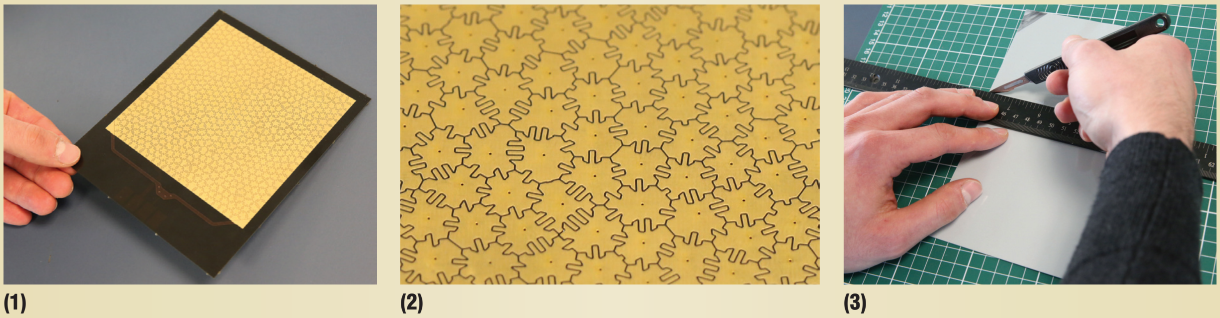
(1) (2) (3)

Figure A. Developing our prototype. (1) The backplane is a regular printed circuit board. (2) The position, size, and shape of each pixel is defined by a series of electrodes running across the top surface of the PCB. (3) The electrophoretic display (EPD) media must be cut to match the overall size of the display.

extra driving circuitry will allow for OLED-based[8] autonomous pixel displays, which would support full color, high resolution, and high framerates. At the same time, we envisage many pervasive display applications where a monochrome electrophoretic display is more than adequate. Such displays are unobtrusive and very low power yet capable of rendering useful digital content.

TOWARD DISPLAYS AS A MATERIAL

Our autonomous pixel prototypes introduce more flexibility in the design of displays by breaking away from the traditional grid-based display architecture. Our ultimate aim is to think of displays as a material rather than components. We'd like to empower designers of physical objects and spaces to craft and shape displays like they can with paper, textile, metals, and plastics. Display material could be tailored using well-established techniques like cutting, tiling, forming, and casting. This direction of research would complement similar efforts in giving sensors material-like properties.[9] The way forward involves implementing the circuitry present in our current prototypes using thin-film transistors on a truly flexible backplane. The resulting backplane would be laminated to the display media to produce a cuttable sheet of plastic containing millions of autonomous pixels.

This display material would be invaluable for creating objects with doubly curved, nondevelopable surfaces. Presently, these nondevelopable surfaces can only be approximated coarsely by tiling display panels; display bezels and visible gaps between the panels diminish the fidelity to which a particular surface can be realized. As illustrated in Figure 4, with display material, it would be possible to create display pieces with custom shapes that can much better approximate a curved surface when assembled. An even more radi-

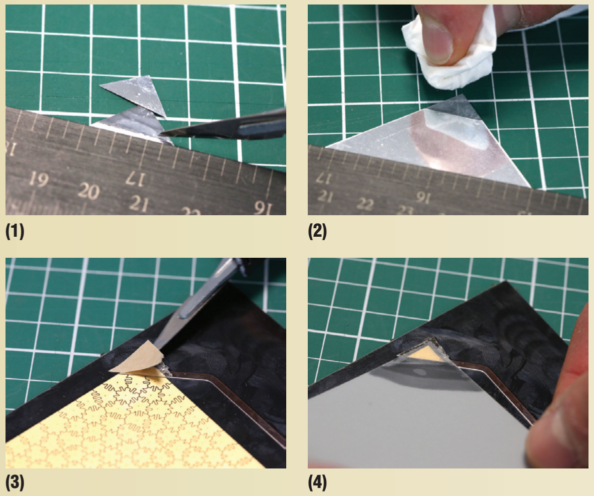

Figure B. Preparing a connection to the indium tin oxide (ITO) layer on the front of the display: (1) Remove the aluminum release sheet from a corner of the media to reveal the EPD material. (2) Remove the EPD material at that location and clean the exposed ITO using isopropyl alcohol. (3) Place a small piece of double-sided self-adhesive tape on the frontplane-driving segment. (4) Remove the remaining aluminum release sheet once the conductive tape is in place.

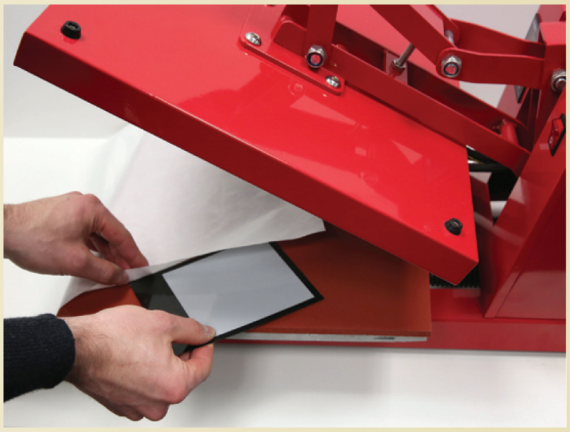

Figure C. The frontplane and the PCB backplane are sandwiched together and bonded by activating the heat-activated-film adhesive.

Driving the display is simply a matter of applying a voltage between any given pixel electrode and the ITO layer. The higher the voltage, the more quickly the white spheres move and the faster the display updates. We found that a 5V differential supports sub-1 second updates. The simplest approach is to drive each pixel directly, for example, using a microcontroller general-purpose input/output (GPIO) line. In this scheme, the ITO layer is first driven at 5 V so that any pixel electrodes that are then connected to 0 V will turn white due to the electric field created. Then, the ITO layer is connected to 0 V, and any pixels that need to become black are driven to 5 V. It's also possible to create more complex addressing schemes; for example, an active matrix display can be built by fitting discrete transistors behind each pixel electrode.

cal possibility is the ability to "spray" autonomous pixels onto arbitrarily shaped objects to make displays in unprecedented forms.

The autonomous pixel architecture described here and the concept of displays as a material are valuable steps in the evolution of digital displays. By lifting the restrictions associated with today's rectangular displays, the ergonomics of the devices and physical environments that incorporate displays could evolve in new ways. Ultimately, we hope that our work, combined with future developments in display

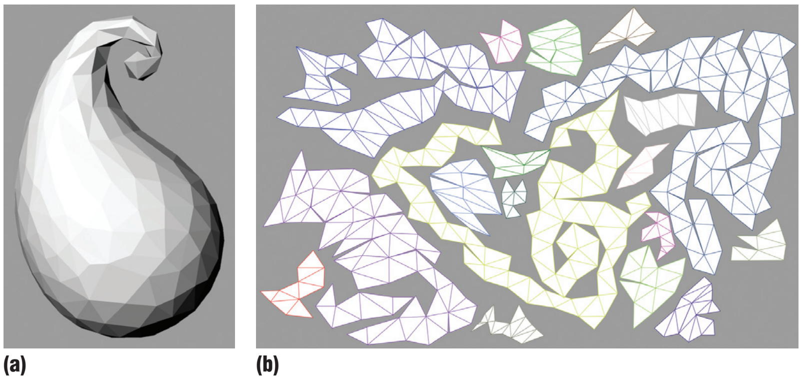

Figure 4. The benefits of display material: (a) Such material could support radical new form factors for displays, such as doubly curved surfaces. (b) You could also expand such a shape into a polygon mesh and cut the display material to the corresponding pattern before folding and forming the material back into the target shape.

technology, will lead to more informative, useful, and appealing devices and spaces. 🅿

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David Sweeney is a creative design technologist at Microsoft Research. Contact him at dasween@microsoft.com.

Nicholas Chen is a researcher at Microsoft Research. Contact him at nchen@microsoft.com.

Steve Hodges leads the Sensors and Devices research group at Microsoft Research, Cambridge UK and is a visiting professor at the School of Computing Science, Newcastle University. Contact him at steve.hodges@microsoft.com.

Tobias Grosse-Puppendahl is a post-doc researcher at Microsoft Research. Contact him at tgp@microsoft.com.

ADVERTISER SALES INFORMATION

Advertising Personnel
Marian Anderson
Sr. Advertising Coordinator
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Fax: +1 714 821 4010

Sandy Brown
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Email: sbrown@computer.org
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Ann & David Schissler
Email: a.schissler@computer.org, d.schissler@computer.org
Phone: +1 508 394 4026
Fax: +1 508 394 1707

Southwest, California:
Mike Hughes
Email: mikehughes@computer.org
Phone: +1 805 529 6790

Southeast:
Heather Buonadies
Email: h.buonadies@computer.org
Phone: +1 973 585 7070
Fax: +1 973 585 7071

Advertising Sales Representative (Classified Line)
Heather Buonadies
Email: h.buonadies@computer.org
Phone: +1 973 304 4123
Fax: +1 973 585 7071

Advertising Sales Representative (Jobs Board)
Heather Buonadies
Email: h.buonadies@computer.org
Phone: +1 973 304 4123
Fax: +1 973 585 7071