Building Functional Prototypes Using Conductive Inkjet Printing

Conductive inkjet printing with a consumer-grade inkjet printer can be used to create conductive circuits, including touch- and proximity-sensitive surfaces and other functional device prototypes. This easy, cheap, and quick process is relevant to a range of pervasive computing applications.

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Pervasive computing research frequently involves the design, deployment, and iteration of novel electronic hardware. An essential element of hardware development is a wiring mechanism of some kind—a way to connect the different circuit elements electrically to provide the desired functionality. Researchers use a range of established and emerging construction tools and techniques to do this.

When used in the correct way, recently developed conductive inks allow researchers to create simple electronic circuits and devices more quickly, cheaply, and easily than before. It's possible to rapidly create touch- and proximity-sensitive surfaces, cut and fold the printed conductive patterns, and augment them with off-the-shelf electronic components and custom-made subcircuits.

Circuit Construction Techniques

Traditionally, the first phase of electronic circuit prototyping often involves a solderless breadboard. This is a convenient way to physically secure components and connect them electrically. It supports quick prototyping and iteration—making it an obvious choice in the early stages of development. Its main drawbacks relate to the size, reliability, and performance of the resulting circuits; to address these, it's often necessary to transition to a printed circuit board (PCB). Not only do PCBs enable physically smaller prototypes, but they support much higher-fidelity and higher-performance designs. PCBs can be made not only from rigid glass epoxy material but also from flexible Kapton substrates. They are more reliable than breadboards, and they lend themselves to larger-scale production—particularly important when it comes to evaluating ideas through deployment in the wild.

On-Demand Fabrication Tools for Custom Circuits

Although PCBs are well suited to mass production, they have several disadvantages in a prototyping context. In particular, the time and expense of producing prototype PCBs isn't ideal considering the rapid iteration often inherent in research. Flexible PCBs are even more problematic, often costing many hundreds of dollars to produce and with turnaround times in excess of a week.

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TABLE 1
Various electronic fabrication processes for a prototype 100 × 100 mm circuit.

	FR4 PCB*	Kapton PCB	Bare Paint†	Silver pen†	Instant inkjet
Number of layers	2	2	1	1	1
Sheet resistance (mΩ/sq)	0.5	1.5	55,000	~35	200
Minimum track width and separation (mm)	0.15	0.15	~1	~1	~0.2
Minimum bend radius (mm)	n/a	1	> 50	> 50	5
Cost (US$)‡	$125	~$500	$1	$5	$2
Production time	4 days	1 week	Minutes to hours		3 mins

*There are a wide range of options for standard FR4 PCBs, such as a layer count up to ~20, sheet resistance down to 0.1 mΩ/sq, track and gap < 0.1 mm, and faster production times, but all these increase expense.
†The cost, sheet resistance, and flexibility of Bare Paint and silver pen circuits depend on trace thickness; production time depends on complexity and printing method.
‡Cost estimates include substrate and ink but exclude equipment.

As an alternative, a number of lab-based PCB fabrication machines are commercially available. These use milling or chemical etching to remove areas of copper from a rigid copper-clad sheet, leaving pads, signal traces, and other conductive structures behind. However, these machines can be awkward to set up, operate, and maintain. Although they often support double-sided designs, adding the necessary electrical "via" connections between layers involves extra equipment and processing; flexible substrates are often not supported at all. As a result, adoption has been limited to date.

Other researchers in the pervasive computing community have explored the use of commercial vinyl-cutting machines in conjunction with adhesive-backed copper foil for single-sided circuit fabrication. This approach is relatively cheap and versatile but it also has several drawbacks: removing unwanted material after cutting is tedious and time-consuming, and thin traces are easily broken.[1]

Conductive Ink and Paint

In subtractive production techniques, unwanted copper is selectively removed from a substrate to leave the desired traces behind. An alternative process is the additive approach of using conductive ink. This has the potential to be cleaner, cheaper, more environmentally friendly, and faster.

To support conductive printing, a variety of conductive inks and paints are commercially available. Carbon-based products like Bare Paint (http://bareconductive.com), targeted at the hobbyist and education sectors, can be hand-painted with a brush. This is quick and easy but results in coarse geometries and layers around 50 μm thick, which can crack when dry. Screen printing may be used, but this introduces a stencil manufacturing step followed by the printing process itself with its associated setup time and ink wastage. The high sheet resistance of the paint, approximately 55 Ω/sq (ohm/sq is the sheet resistance from one edge of a square shape of material to the opposite edge), makes it hard to use traces narrow enough to support a reasonable density of components.

Silver-based products overcome the poor sheet resistance of carbon-based paint. For example, the CircuitWorks MicroTip Conductive Pen from Chemtronics (www.chemtronics.com) can result in a sheet resistance of much less than 0.1 Ω/sq. However, the relatively large silver flakes suspended in the ink make it hard to create patterns less than 1 mm wide. The particle size also causes the pens to clog easily, and because the traces are relatively thick they are also quite brittle if flexed. Also, as with Bare Paint, inkjet printing is not possible.

Conductive Inkjet Printing

The various circuit construction techniques just described trade off versatility, performance, cost, and speed of production, as summarized in Table 1. However, another process, namely conductive inkjet printing, has the potential to provide a useful alternative.

Commercial Printing Techniques

Inkjet printing of conductive traces has become increasingly established over the past decade. Commercial services use highly specialized equipment and materials to achieve this, but once these are in place, the printing process requires little setup, is clean, and results in high fidelity and repeatable circuits. In earlier work,[2] we used a roll-to-roll conductive inkjet printing process pioneered by a company (www.conductiveinkjet.com) in Cambridge, UK, to build a versatile large-area underfloor sensing surface for a pervasive computing application. The roll-to-roll manufacturing process results in arbitrarily long, high-resolution flexible copper circuits with low sheet resistance of 20–50 mΩ/sq. However, as with PCBs, the turnaround time limits iterative prototyping.

Another approach to conductive inkjet printing is the use of recently developed silver nanoparticle ink. This ink has tiny silver particles less than 100 nm in diameter suspended in an emulsion. Like the roll-to-roll process, this allows relatively high-resolution conductive features to be created quickly, easily, and repeatably. It also results in consistent, thin layers of material, alleviating cracking. However, silver nanoparticle inks have, until recently, required a highly specialized inkjet printer such as a Fujifilm Dimatix DMP-2800 (www.fujifilmusa.com), which costs tens of thousands of dollars. Coupled with this, the printed ink is not immediately conductive because the silver nanoparticles are enclosed in a polymer shell designed to prohibit agglomeration prior to deposition. In order to form mutual connections among the metal particles, a thermal sintering step involving several hours in an oven at more than 150°C is necessary.

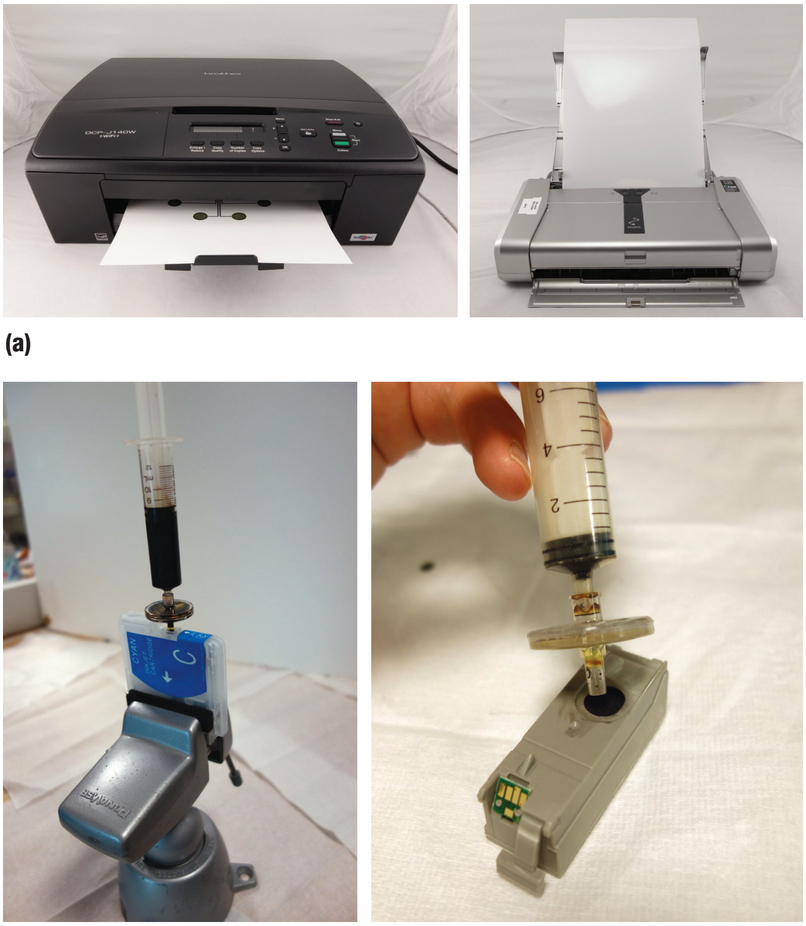

Figure 1. Using domestic printers for instant inkjet circuit fabrication: (a) the Brother DCP-J140w and Canon iP100 printers, and (b) third-party inkjet cartridges filled with Mitsubishi silver nanoparticle ink using a syringe and disposable filter.

TABLE 2
Optimal printer driver settings for our two printers.

Parameter	Brother DCP-J140w	Canon iP100
Media type	Glossy photo paper	Photo Paper Plus Glossy II
Print quality	Best	Custom → quality: 1
Color mode and effects	Vivid	Vivid photo
Color enhancement	Enable	n/a
Color density/intensity	+2	Manual → defaults
Improve pattern printing	Enable	n/a

Instant Inkjet Circuits

We recently introduced a new approach to the rapid prototyping of fully custom printed circuits using a more accessible form of inkjet printing.[3] This work leverages a new chemical sintering method that circumvents the need for time-consuming and potentially damaging thermal sintering.[4] Key to this is the use of a special silver nanoparticle ink that dries immediately at room temperature, thereby forming an instantly conductive layer. We deposit the ink using an inexpensive off-the-shelf consumer-grade inkjet printer.

The combination of easy-to-use ink with an affordable printer enables a wide range of users to adopt a highly explorative and iterative development process for new electrical circuits in a way that existing materials, tools, and techniques—such as breadboards, printed circuit boards, and conductive paints—do not. We believe that this process, which we call *instant inkjet printing*,[3] has the potential to facilitate electronic prototyping in the same way that the 3D printer has done for mechanical prototyping.

Printers, Ink, and Substrates

Central to the fabrication of instant inkjet circuits is the printer itself. When we started this research in 2012, we chose a Brother DCP-J140w, which we still use regularly. We now also use a Canon PIXMA iP100 Mobile Photo Printer, chosen primarily because of its small size and portability, although it's also a little faster and supports a higher print resolution and repeatability than the Brother printer. However, it doesn't deposit as much ink, resulting in traces with higher resistance. At US$160, it's also more expensive than the $80 Brother printer. Figure 1 and Table 2 provide details about these printers and how to use them for instant inkjet circuit printing.

We imagine that other piezoelectric inkjet printers will also be suitable for our approach. But one very practical concern is the availability of empty cartridges, typically provided by a third party company—we don't reuse the original ink cartridges because contamination from residual ink would result in poor sintering. Because the conductive ink is supplied in a bottle, we must transfer it into empty cartridges using a syringe and disposable filter (see Figure 1b). Desktop inkjet printers often use at least four different cartridges: cyan, magenta, yellow, and black (CMYK), and we typically load conductive ink into all of these. By printing in "photo mode," the printer driver uses CMY simultaneously to generate a solid black. This maximizes the amount of ink deposited.

Ink is of course another key element of the instant inkjet printing process. Characteristics such as viscosity, surface tension, density, and particle size are all important to ensure that drops of just a few picoliters of ink are released smoothly from the piezoelectric inkjet nozzles. We have almost exclusively used NBSIJ-MU01 silver nanoparticle ink from Mitsubishi Paper Mills, which has a viscosity of 2–3 centipoise (cPs), a surface tension of 30–35 milliNewtons per meter (mN/m), a density of 1.2 g/ml, and a 20 nm particle size. It is water based and contains 10- to 40-percent ethylene glycol by weight, with 10- to 20-percent silver content by weight. At the time of writing, NBSIJ-MU01 costs either $250 or $500 for 100 ml, depending on the country of purchase, Japan or US respectively. This translates to around $60 or $120 per sq. meter, or 6–12 US cents/meter for a 1 mm wide trace. Other self-sintering conductive nanoparticle inks are available from Methode and Novacentrix while AgIC (http://agic.cc), a spin-off from The University of Tokyo, plan to deliver conductive marker pens and printing kits in 2014.

The third critical element is the printing substrate. Resin-coated paper optimized for the ink we use is available from Mitsubishi Paper Mill as part number NB-RC-3GR120 at around US$1 per A4 sheet. Transparent and white polyethylene terephthalate (PET) films—NB-TP-3GU100 and NB-WF-3GF100, respectively—are also available at around $1.50 per A4 sheet. High-quality glossy photo paper from online suppliers such as Kodak, Fujifilm, and Gassai Pro can also be used, although the ink does not adhere so well in our experience.

Things to Avoid

Commissioning an instant inkjet printing setup is remarkably straightforward. However, having worked in this space for some time, we have experienced a number of pitfalls that we bring together here to assist others.

We initially expected the print head nozzles to regularly become clogged based on expectations set by the ink providers. For example, both Methode and Novacentrix suggest that the heads and entire print pipeline should be cleaned thoroughly using an aqua-ammonia solution if the printer is left unused for several hours or more. However, we have not experienced any major clogging issues in our work to date using several Brother DCP-J140w printers for around 18 months. However, we found there was a slight decrease of conductivity with the Canon iP100 printer over time, which we believe is due to Canon's bubble jet technology, where heat is applied to the ink. We don't do any regular printer maintenance other than occasional head cleaning using the built-in automated function, often leaving a printer unused on the lab bench for several weeks at a time. We believe that the use of NBSIJ-MU01, which is optimized for consumer-grade piezoelectric inkjet printers, is important. Of course, the ink and printer suppliers don't recommend use of their products in the way we describe here, so there are no guarantees.

For comparison, we also evaluated Mitsubishi silver nanoparticle ink NBSIJ-FD02, which is optimized for Dimatix printers (viscosity < 10 cPs, surface tension 25–35 mN/m, and density 1.3 g/ml). This initially worked fine in a Brother DCP-J140w, but after several months the printouts became increasingly "blurry" and conductivity dropped, to the point of unusability. We assume that this is ultimately due to unwanted buildup of ink inside the print mechanism. We have also evaluated Conductive Inkjet Ink 9101 (viscosity 3.5 cPs, surface tension 55 mN/m, density 1.2 g/ml) from Methode Electronics, in conjunction with an Epson WF-7010 as part of Methode's DK9101 conductive ink development kit. Methode suggests that a sheet resistance of 25 mΩ/sq and a feature size of 75 μm are possible. However, we again found that clogging was an issue given our unorthodox approach.

Inkjet printer paper is typically finished with a thin porous coating, which plays a critical role in drying the ink quickly while leaving the nanoparticles to sinter on the surface. Surface smoothness is also an important factor in establishing the nanoscale conductive structure. We have found that a number of substrates designed for desktop inkjet printing are not suitable for instant inkjet circuits, including lower-quality paper and printable fabrics. In our tests, many of these resulted in a sheet resistance in excess of 100 kΩ/sq. It's also worth noting that dust particles on the paper affect the printing process, so paper stock should be kept clean.

Safety

Silver nanoparticle ink is a relatively new material, and it's important to observe the guidelines in the supplied material safety datasheet. Although NBSIJ-MU01 is a water-based ink and can theoretically be washed away, we have found that it can stain surfaces if not cleaned thoroughly and quickly. We are always particularly careful when handling the ink, being sure to wear protective gloves to prevent contact with the skin and therefore avoid any risk of nanoparticles being absorbed. Similarly, goggles will prevent any accidental eye contact.

The ink instantly dries to the touch when it's printed onto a suitable substrate, so once the silver nanoparticles have sintered into a thin layer of solid silver, we believe there are fewer concerns. It's possible to deposit too much ink, resulting in a dark grey coating of unsintered ink. This is less of an issue with narrow traces because the ink dries much more readily, but it can be a problem with larger areas of printed ink. The solution is to reduce the amount of ink deposited by adjusting the RGB values in the design being printed.

Printed Circuits in Use

The conductive structures produced by inkjet printing can be augmented in a variety of ways to support the construction of prototype pervasive computing devices and systems. Having characterized the performance of instant inkjet printed conductors, we describe a number of these techniques here.

Print Quality

Sheet resistance is perhaps the most important characteristic of printed conductors. We characterized this by measuring the size and resistance of several printed shapes, using cross measurements when the aspect ratio was small. When depositing NBSIJ-MU01 onto NB-RC-3GR120 paper using the Brother printer, we see a sheet resistance of 0.21 Ω/sq as soon as the print is finished; that is, the circuit is immediately ready to use. The measured resistance drops to 0.19 Ω/sq over 10 hours,[3] as the ink dries completely. This matches the manufacturer's claimed figure of under 200 mΩ/sq. We have not been able to equal this using the Canon printer, where we measured the sheet resistance immediately after printing to be 0.36 Ω/sq and again saw a marginal improvement over a 10-hour period.

In addition to low sheet resistance, we also want high resolution and repeatability to allow detailed features to be printed. In this regard we found the Canon printer to be more effective, although in both cases the printed line is 50 to 100 μm wider than specified in the design software. We assume this is due to a combination of inaccuracies introduced by the printer driver pipeline and the printer itself.

We used a scanning electron microscope to measure the thickness of the ink deposited with the Brother printer and found it to be 300 nm. We experimented with overprinting to create thicker traces and found that resistance decreases by 40 percent after a second pass and then another 16 percent following a third pass.[3] Unfortunately, the tray-based paper-loading mechanisms common in low-cost desktop inkjet printers typically have an alignment variation of 0.5 mm at best, so this technique is only practical for wider traces.

Combining with Other Materials and Traditional Electronics

When a conductive pattern has been printed, it's usually necessary to integrate it with other materials or traditional electronic circuitry. Unfortunately, conventional soldering techniques aren't suitable because solder typically melts at a higher temperature (for example, 180°C) than is tolerated by the substrate and its chemical coating. Low-temperature solder variants are available, and these mitigate this issue, but in our experience soldering is still largely unsatisfactory.

Sometimes a simple mechanical connection will suffice. For example, we have connected coin-cell batteries to a printed circuit simply by holding the electrodes against the substrate with a bulldog clip. A similar technique can be used with the leads of through-hole electronic components like resistors and LEDs, and we have also found that flat-flex connectors can be readily used to interface with instant inkjet circuits by printing and cutting the substrate appropriately.

Another alternative is to mechanically and electrically attach electronic components to the printed substrate using conductive epoxy. We use MG Chemicals 8331 epoxy—a two-part adhesive, loaded with silver particles, that begins to harden 10 minutes after the two pastes are mixed. The conductivity increases as the epoxy cures, reaching a maximum after several hours at room temperature.

Conductive epoxy is well suited to connecting wires and individual components. However, mixing and applying it tends to be fiddly, messy, and laborious. An alternative that's an excellent match for instant inkjet circuits is electrically conductive double-sided tape. We have found 3M Electrically Conductive Adhesive Transfer Tape (ECATT) 9703 to be highly suitable because of its anisotropic electrical conductivity.[3] The tape is filled with conductive particles that provide interconnection through the tape's thickness (along its "Z-axis"). However, the particles are spaced far enough apart for the product to be electrically insulating in the plane of the adhesive. Therefore, the tape can be used to electrically connect and at the same time mechanically bond electronic components to an inkjet-printed substrate. The "resolution" of the tape supports a track and gap of around 0.2 mm, which is a good match with instant inkjet circuits; in our experience, this introduces negligible resistance in comparison with typical printed trace resistances.

Circuit Stickers

In theory, ECATT provides a great way to attach surface-mount electronic components directly to an inkjet-printed circuit. However, in practice the contact area between individual pads and the conductive traces is too small to make a reliable connection. Also, the total contact area between the component itself and the substrate is often small—either because the component body is raised or because it's simply too small—which means that components aren't secured robustly enough and easily become detached.

To overcome this, we have developed an approach we call *circuit stickers*.[5] We start by manufacturing a range of small PCBs that contain individual components and simple subcircuits on one side, and surface-mount pads on the reverse side. These are used as

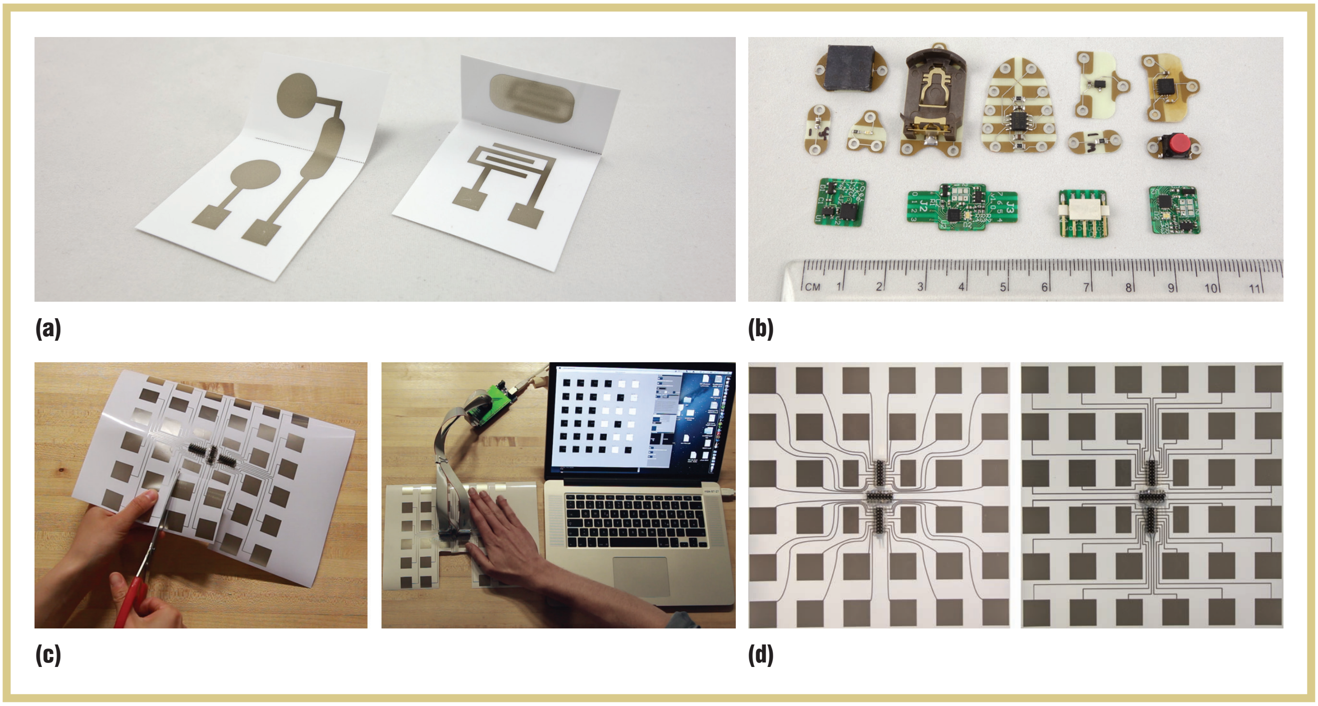

Figure 2. Ways to use instant inkjet printing. (a) Simple push-button fold switches. The design on the left has a restricted bend radius on the fold because the conductor mustn't be damaged, whereas the design on the right allows for a sharp fold in the substrate. (b) Example circuit stickers. (c) Ad hoc cutting of an inkjet-printed touch sensor supports physical prototyping. (d) Two complementary wiring topologies can be overlaid to enhance robustness to cutting.

building blocks for the electronic functionality required for a prototype, the idea being to integrate several of them into a design using an instant inkjet-printed substrate to provide the desired electrical connections between them. ECATT is applied to the bottom of each PCB to create the sticker circuit, and this is then stuck to matching conductors on the printed substrate.

We imagine that a small number of general-purpose sticker circuits could support quite a range of applications. To date we have fabricated a variety of stickers, including LEDs, piezo sounders, hall-effect sensors, accelerometers, and push buttons (see Figure 2).[5]

Circuit stickers can be used in conjunction with a battery (which can also be stuck down to the substrate in many instances) to create a standalone device, or they can be interfaced to a microcontroller such as Arduino or .NET Gadgeteer.[6] We have found circuit stickers to be a versatile and low-cost way to support quick and easy construction of physically flexible interactive prototypes.

Touch, Proximity, and Other Sensing

Capacitive touch sensing has become a well-established interaction paradigm for all manner of digital devices. As well as integrating electronic circuitry as described earlier, it's possible to use inkjet printing technology to quickly and easily fabricate uniquely shaped capacitive sensing electrodes optimized for a particular application. To facilitate this, we have built a circuit sticker that incorporates a Freescale MPR121 touch sensor IC and supports up to eight different touch electrodes.

It's also possible to measure the presence of materials such as liquids and metallic objects using a printed interdigitated capacitor. As these materials come into proximity with the capacitor, an increase in capacitance can be detected.[3] These scenarios are demonstrated later in this article.

Physical Prototyping

In addition to a traditional prototyping workflow where a circuit is designed on-screen using a CAD tool before it's inkjet printed, we have also developed a physical prototyping process.[7] This involves the preproduction of a standardized printed conductive pattern, which we subsequently manipulate and modify by hand. As long as we maintain a minimum bend radius—5 mm in our tests with NBSIJ-MU01 and the Brother printer—conductivity is not compromised. This customization makes for a much more immediate and organic "craft-like" experience.

As well as bending, instant inkjet circuits can also be cut with scissors or a craft knife, readily supporting direct customization of the size and shape of a prototype. Cuts in-between conductive areas don't usually affect operation of the circuitry, but we have also developed some principles and guidelines that enable ad hoc customization even when the conductors are cut.[7] We are primarily targeting multitouch sensing applications because we see this as a key application for instant inkjet printing.

In order to make a printed touch sensor sheet that can be customized by cutting it into a particular shape, we use two layers with a different layout for each. The first is a star topology, where traces extend radially from a central connector to individual touch-sensitive electrodes. This is well suited to convex sheet shapes such as triangular, rectangular, and ellipsoidal, but it provides only limited support for nonconvex shapes. A second complementary topology, the tree, addresses this. Again, we wire each electrode to a central connector, but in this case we first route the wires vertically and then horizontally, as shown in Figure 2d.

One final way to customize instant inkjet-printed prototypes is to use a regular felt pen filled with silver nanoparticle ink. This can be used to add arbitrary conductive traces at any time in the design process.

Example Applications

To illustrate how the ideas and results presented in this article can be used in a pervasive computing research context, we present some of the applications we have built using instant inkjet printing.

Our technique provides an effective alternative to the established approaches for creating custom electrode patterns—a recurring requirement in the research community as demonstrated by projects such as DiamondTouch,[8] Touché,[9] and Midas.[1] We have successfully built several different touch sensor configurations using our touch-sensing circuit stickers, as well as developing the cuttable touch-sensing technology described previously.

Furthermore, we have built on several techniques that we originally developed as part of a printed underfloor sensing system[2] to create a mixed-modality touch-sensing surface compatible with instant inkjet printing.[10] Our prototype is able to detect proximity as well as capacitive touch by switching between traditional capacitive sensing, AC hum detection, and a transmit-and-receive mode of operation, using the same electrode pattern for each. AC hum detection can be useful for detecting human presence in indoor environments, because the human body naturally picks up and re-radiates mains noise. In transmit-and-receive mode, one set of electrodes is stimulated with an AC signal while a second set picks up the same signal. If part of a user's body is in contact with the transmitting electrode, this increases signal transfer to nearby receivers. Certain types of deformation of the printed surface can also be detected using the transmit-and-receive mode, as shown in Figure 3a–c.

Finally, we have explored three more pervasive computing prototypes using instant inkjet circuits. In the first, we created an instant inkjet-printed control for an electric ukulele (Figure 3d).[11] Using two inkjet-printing passes, one for silver nanoparticle ink and a second for regular color ink, and then laser-cutting the outline and surface details, we created an aesthetically driven sensing surface that is part of the musical instrument itself while also functioning as a controller. In the second test, to demonstrate the potential in a wearable computing context, we constructed a sensing glove where accelerometer-based circuit stickers are attached to the tips of three fingers by way of a flexible circuit printed on PET film and subsequently laser-cut to fit the glove (Figure 3e).[5] Finally, we tested the versatility of capacitive sensing by creating a liquid-level sensor (Figure 3f) using an inkjet-printed interdigitated structure.[3] After printing the substrate and cutting out the sensor, we laminated it to make it waterproof. There was a linear mapping between liquid level (0–100 mm) and capacitance (0–1.8 nF).

As part of our own research, we have used many of the techniques described in this article to create and iterate several electronic prototypes. We hope that others in the field of pervasive and ubiquitous computing will be inspired to look for opportunities to leverage instant inkjet printing and fabrication in their own work.

A number of topics of further research and development have come to light, and we're keen to explore many of these. One major limitation of our work so far is the single-layer nature of the printed circuits we are creating. We're actively exploring possibilities for creating double-sided and multilayer printed circuits. We're also interested in making stretchable printed circuits[12] and would like to build on our earlier exploration of 3D printed conductors[13] and the work of others in this exciting area of research to extend this concept beyond planar printing.

To date, prototyping has been a focus of our work with instant inkjet circuits. However, we are also interested in the idea of using the same techniques for production. In particular, the accessibility of the technique would allow it to be used for low-volume and highly customized production, potentially creating interesting new business opportunities.

We would like to evaluate the performance of other silver nanoparticle ink formulations from Methode and also products from Novacentrix. For example, other researchers have successfully used Novacentrix JS-B35P ink in conjunction with an Epson printer.[14] Ideally we would like to facilitate provision of the materials needed for instant inkjet printing to researchers and

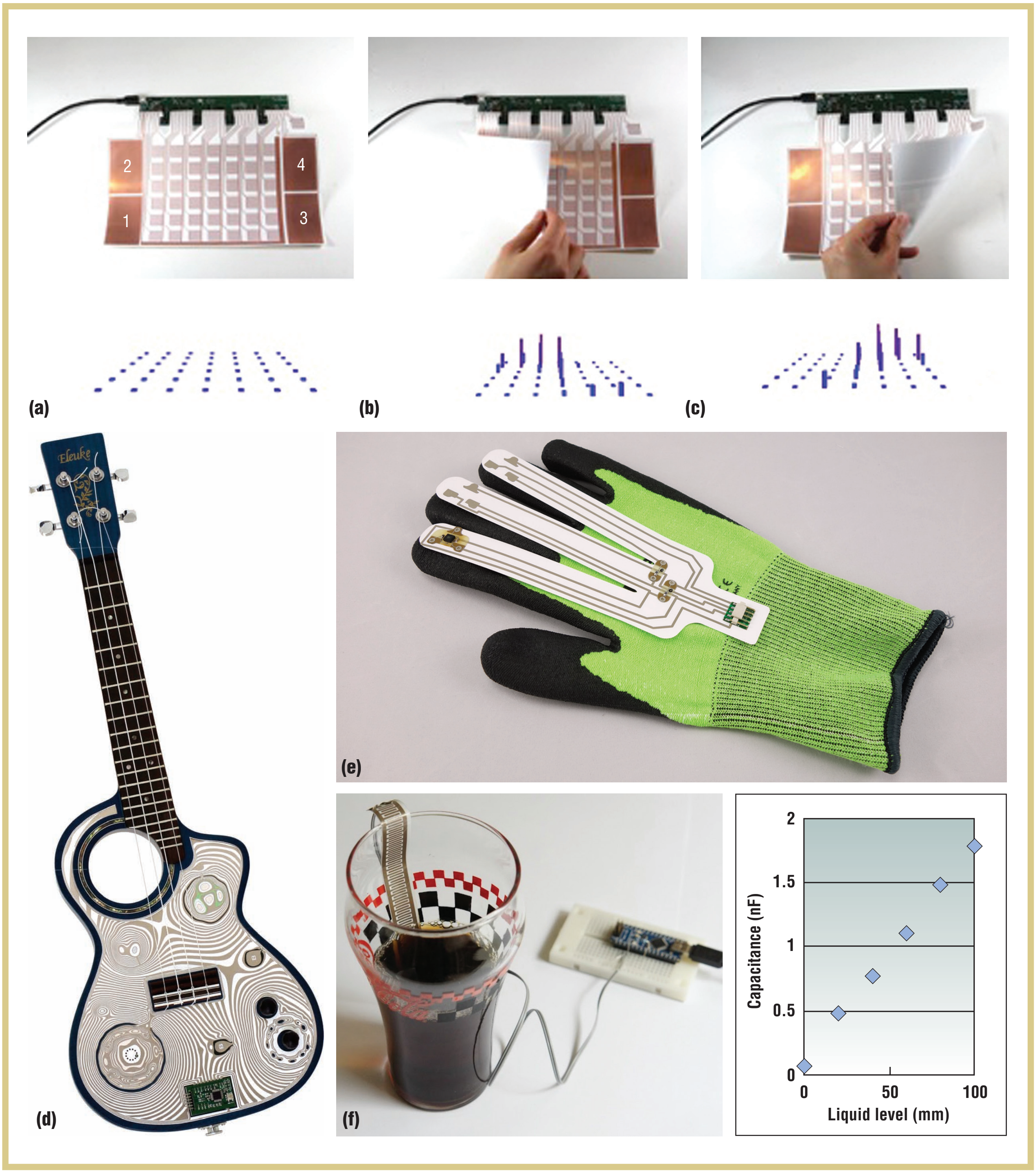

Figure 3. Example applications. (a) This electrode configuration detects deformation of a flexible substrate where electrodes 1 and 3 are active transmitters. (b) As the left-hand corner is folded over, the sensing electrodes in the center of the sheet detect the signal emitted by electrode 1. (c) The right-hand side is folded over. (d) This electric ukulele has a custom-crafted sensing surface. (e) This fingertip-sensing glove prototype is circuit-sticker-based. (f) An instant inkjet-printed capacitive liquid-level sensor. After printing the substrate and cutting out the sensor, we laminated it to make it waterproof. As shown in the graph, there was a linear mapping between liquid level (0–100 mm) and capacitance (0–1.8 nF).

hobbyists alike so that they are readily and cheaply available to buy. Our ultimate objective with this work is to illustrate when and how printed conductive circuits can be used, empowering and motivating others to replicate, use, and build on our work.

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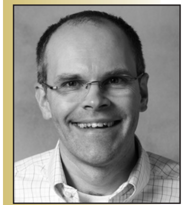

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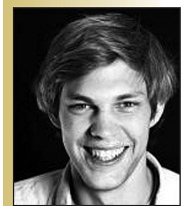

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