Instant Inkjet Circuits: Lab-based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices

Yoshihiro Kawahara
The University of Tokyo
7-3-1 Hongo, Bunkyo-ku,
Tokyo, Japan
kawahara@akg.t.u-tokyo.ac.jp

Steve Hodges
Microsoft Research Cambridge
Cambridge, United Kingdom
Steve.Hodges@microsoft.com

Benjamin S. Cook
Georgia Institute of Technology
Atlanta, Georgia, U.S.A.
benjamin.cook@gatech.edu

Cheng Zhang
Georgia Institute of Technology
Atlanta, Georgia, U.S.A.
chengzhang@gatech.edu

Gregory D. Abowd
Georgia Institute of Technology
Atlanta, Georgia, U.S.A.
abowd@gatech.edu

ABSTRACT
This paper introduces a low cost, fast and accessible technology to support the rapid prototyping of functional electronic devices. Central to this approach of 'instant inkjet circuits' is the ability to print highly conductive traces and patterns onto flexible substrates such as paper and plastic films cheaply and quickly. In addition to providing an alternative to breadboarding and conventional printed circuits, we demonstrate how this technique readily supports large area sensors and high frequency applications such as antennas. Unlike existing methods for printing conductive patterns, conductivity emerges within a few seconds without the need for special equipment. We demonstrate that this technique is feasible using commodity inkjet printers and commercially available ink, for an initial investment of around US$300. Having presented this exciting new technology, we explain the tools and techniques we have found useful for the first time. Our main research contribution is to characterize the performance of instant inkjet circuits and illustrate a range of possibilities that are enabled by way of several example applications which we have built. We believe that this technology will be of immediate appeal to researchers in the ubiquitous computing domain, since it supports the fabrication of a variety of functional electronic device prototypes.

Author Keywords
Inkjet-printing; Conductive Ink; Capacitive Sensors; Rapid Prototyping; Digital Fabrication.

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Figure 1. Silver nanoparticle ink is injected into an empty cartridge and used in conjunction with an off-the-shelf inkjet printer to enable 'instant inkjet circuit' prototyping.

General Terms
Design; Experimentation; Measurement.

INTRODUCTION
It almost goes without saying that wiring is an intrinsic element of any kind of functional electronic device. It supports the distribution of power, provides digital and analog signal interconnection, enables the flexible positioning of components such as sensors and actuators, and can even be used as a basis for the electrical components themselves in the case of switches, moisture sensors, capacitive touch sensors, antennas and so on.

Perhaps the two most widely-used wiring solutions for prototype electronic devices are solder-less breadboards and printed circuit boards (PCBs). Both of these provide a convenient way to mount components, interconnect them and distribute power. The main advantage of breadboards is that they support very quick prototyping and iteration of a design which means they are an obvious choice in the early stages of UbiComp device creation. However, they have drawbacks in terms of size, reliability and performance which frequently make a transition to a PCB prototype inevitable. The custom nature of PCBs means that they are more versatile, can support physically smaller prototypes and are usually more robust. They also support much higher fidelity design which allows experimentation with conductive structures that have special sensing and/or radio frequency (RF) properties.

Whilst PCBs are well-suited to mass-production, they have several disadvantages in a prototyping context. In particular the time and cost involved in having them manufactured is often at odds with the rapid iteration inherent in research. Online PCB production services have advanced a lot in recent years, but sending a design away and waiting for a couple of days is still very different from making a board in the lab and trying it out just hours later. Whilst some lab-based PCB fabrication machines exist, they are not cheap, can be fiddly to set up and maintain, and as a result have only enjoyed limited adoption to date. If a particular project requires a flexible substrate (so called flex-PCBs) this is even more problematic, with simple prototypes often costing many hundreds of dollars to produce with turnaround times in excess of a week. And until now, producing flex-PCB prototypes in the lab has not really been feasible.

Our objective is to provide the means for researchers to print flexible circuits quickly, easily and cheaply, in a lab environment. In this way we hope to introduce an intermediate alternative to breadboards and custom PCBs which will have clear benefits in certain UbiComp prototyping scenarios.

This paper describes our new solution for printing circuits which are flexible both in the physical sense and in terms of the applications which they support. Following a review of related work in this area, we describe our 'instant inkjet circuit' approach in some detail for the first time. We share the best practices we have developed and characterize the results we have seen. We then present a number of applications for this technology which we think will be of interest to other researchers in the broad field of ubiquitous computing. We end by discussing a number of issues that have come to light during this research and future directions we would like to pursue. Our ultimate aim is to empower and motivate others to replicate, use and extend our work.

RELATED WORK

UbiComp research which motivates this work

Whilst physical rapid prototyping tools such as laser cutters and 3D printers have advanced tremendously in recent years and are now standard tools for UbiComp research, we feel there is still an opportunity for equivalent advances in electrical rapid prototyping. Our work is inspired by a number of innovative ideas presented in the UbiComp-related research literature, where we feel that more powerful prototyping tools for electrical circuitry may have been valuable in facilitating faster and wider exploration. We start by reviewing some of these projects to illustrate these opportunities. We then present the current state-of-the-art in tools and materials for quick electrical prototyping.

The domain of 'digital crafting' – manually constructing digital artifacts from a range of less conventional materials to create artistic and engaging functional devices – is becoming popular. For example in Pulp-Based Computing [5], the authors present a way of embedding conductors and electronic circuitry into a single sheet of hand-made paper. Other relevant projects from the literature include Kit-of-no-parts [16] and Electronic Popables [17]. We recognize that digital crafting is by its nature a quite manually intensive process, but none-the-less we feel that an accessible electrical circuit prototyping tool would be a valuable extension to the crafter's toolbox.

Midas is a tool which supports the design of customized conductive patterns for touch sensing applications, with the aim of making it easier to add interactivity to prototype devices [20]. Midas automatically generates layout files with the appropriate sensor pads and routed connections. The authors demonstrate two different ways of converting these layouts into physical prototypes, but also describe the limitations of each of these. They point to conductive inkjet printing as an ideal solution, if it were more accessible to researchers.

In [10], Gong et al. propose the use of a relatively new roll-to-roll conductive inkjet printing process to build a scalable and versatile sensing surface for UbiComp applications. One of the contributions of this work was the use of relatively cheap fabrication of large-area printed circuits to distribute sensors including printed antennas in the environment – in this case under the floor. In order to achieve acceptable performance in terms of resolution and conductivity, the authors had to outsource fabrication, and even though a local company had the expertise and equipment to support this, it was both expensive and time-consuming.

Wimmer et al. propose a novel deformable touch-sensing surface using time domain reflectrometry [21]. This approach is unique in the sense that touch is detected as an impedance change in a pair of conductive lines. Perhaps the biggest limitation of this approach is the cost and size of the time domain reflectometry equipment necessary to accurately distinguish small time difference of less than 50 ps, but another limitation is the form of the conductive lines; being able to print these to suit a particular application would be an interesting concept. Tactile Tape is a flexible low-cost tape for touch sensing [12]. The tape consists of three layers (resistive, spacer and conductive) and functions as resistive one-dimensional single-point touch sensor. Since it is fabricated using a metal sheet the design cannot be readily modified. Again, a tool for rapidly prototyping conductive circuits would facilitate this.

Other research explores the use of RFID tags for battery-less sensing, for example detecting the level of liquid in a drinking glass [3] or detecting when an RFID tag (and the goods it is tagging) has been subjected to temperatures outside an acceptable range [4]. In both of these examples the authors report that it would be beneficial to explore custom RFID tag antenna designs to further explore the design space and the potential of their approaches.

As mentioned above, the aim of our work is to support scenarios like these by providing an accessible, cheap and quick method for printing arbitrarily-shaped conductors onto convenient materials, both rigid and flexible.

On-demand fabrication tools for custom circuits

PCB milling machines such as the desktop LPKF ProMat S-Series [14] provide a reasonably accessible route to rapid-prototyping circuit boards in a lab setting. These machines remove areas of copper from a copper-clad sheet of rigid PCB material to create pads, signal traces and conductive structures. Compared with conventional fabrication methods based on a chemical etching process, PCB milling machines are relatively fast and convenient. However, it still takes on the order of an hour to set up and mill a board, maybe longer depending on its size and complexity, and it is a relatively noisy and messy process. Moreover, it is very difficult to mill flexible substrates.

An alternative approach is the use of a commercial vinyl cutting machine – essentially a plotter with a cutting knife instead of a pen – in conjunction with adhesive-backed copper foil. Other UbiComp researchers have pointed out that this approach is relatively cheap (e.g. US$200 for the machine, around US$10 per meter for the film). It is also versatile due to the high conductivity of copper and the physical flexibility of the adhesive foil [20]. However, the subtractive nature of the process has several weaknesses: removing unwanted material after the cutting is complete is tedious and time-consuming, and thin traces can break when the material around them is removed [20].

A third alternative which is frequently used in industrial environments is inkjet printing. Based on recently developed silver nanoparticle inks such as the Xerox 'silver bullet' [9] this technology supports great versatility in terms of the conductive structures which can be created. This 'additive' approach to production is very attractive because it overcomes most of the disadvantages of the 'subtractive' milling and cutting processes described above. The main drawback of this fabrication method is the price of the equipment. A highly specialized inkjet printer is typically used, such as a FUJIFILM Dimatix DMP-2800 [8] which costs several tens of thousands of dollars. Also, the printed ink is not initially conductive because the silver nanoparticles have a polymer shell which prohibits agglomeration while in suspension. Once deposited, the ink must be sintered in an oven at more than 150 °C for several hours in order to form mutual connections among the metal particles. Not only does this limit the substrates that can be used and require additional equipment, it also dramatically reduces the speed with which it is possible to produce prototypes.

Sintering-free Conductive Ink and Paint

Recent advances in materials science have resulted in a variety of commercially-available conductive inks and paints which do not require sintering and which can be applied cheaply and easily. Bare Paint [2] and related products are already popular among hobbyists and artists, but unfortunately the properties of these paints mean that they are not suitable for on-demand rapid prototyping in many of the scenarios we are aiming to support. For example, their high sheet resistance (e.g. 55 $\Omega/\Box$[1]) makes it virtually impossible to use narrow traces or printed antennas. Moreover, because of their high viscosity, screen printing must be employed instead of inkjet printing in order to print precise patterns. Unfortunately, screen printing requires a time-consuming and expensive process of making a screen and stencil, and requires large amounts of ink which are ultimately wasted. Also, when hand painted with a brush, the paint layers become thick (for example around 50 μm) and this means they crack readily which reduces robustness.

Conductive ink pens are popular with electronics professionals and hobbyists. These are designed for the manual re-work of electrical circuits to fix breaks in electrical conductivity. For example, the CircuitWorks MicroTip Conductive Silver Pen from Chemtronics [6] has a line width of 1 mm and sheet resistance of less than 0.1 $\Omega/\Box$. However, the main drawback of this technology is the relatively large size of the silver particles which are suspended in the ink in order to make it conductive. This makes it hard to create patterns less than 1 mm wide. It is also impossible to deposit the thin, consistent layer of ink required for flexible circuitry, so the traces are very brittle.

In summary, we believe there is an opportunity to introduce a new approach to the rapid prototyping of fully-custom printed circuits. Just as rapid mechanical prototyping tools such as laser cutters and 3D printers have enabled researchers to embrace a highly explorative and iterative approach to projects which require prototype mechanical elements, we aim to support this for electrical elements in a way that the existing materials, tools and processes – things like breadboards, printed circuit boards and conductive paints – do not.

NEW CONDUCTIVE PRINTING MATERIALS AND TOOLS

Recently, a new sintering method called chemical sintering was developed [22]. This circumvents the need for time-consuming and potentially damaging thermal sintering and thereby dramatically reduces barriers to using conductive inkjet printing in a research laboratory setting. Nonetheless, it maintains all the advantage associated with established inkjet circuit production. In this section we describe the particular materials and tools we have found to be useful for leveraging this chemical sintering process.

Ink which supports chemical sintering

When silver nanoparticles smaller than 0.1 μm are dissolved in a solvent consisting of polymer latex and a halide emulsion, conductivity appears several seconds after the solution is dried. It has also been shown that when the dried pattern is exposed to moist air even better conductivity results. Surprisingly, the physical dynamics underlying this chemical reaction are still being explored by materials scientists, but the received wisdom is that the polymer latex and silver nanoparticles form a 3D structure and the formation of interconnections among the silver nanoparticles is accelerated

[1] 1 $\Omega/\Box$ is the unit used to represent sheet resistance. This unit is dimensionally equal to an ohm. It is loosely thought of as "ohms per aspect ratio".

by the halide. These are then stabilized by reintroduction of water [22].

For the ink to be smoothly released from an inkjet printer nozzle, the viscosity, surface tension, volatility, and particle size must be optimized. Through experimentation we have found that recently commercialized silver nanoparticle ink from Mitsubishi Paper Mill, part number NBSIJ–MU01, has an appropriate dispersing medium for some desktop inkjet printers. At the time of writing, NBSIJ–MU01 costs around JP ¥20,000 per 100 ml when purchased directly from Japan. This translates to around US$50/$m^2$ or 5 US cents per meter for a 1 mm wide trace[2].

Methode electronics, Inc. produces a range of four similar inks, Conductive Inkjet Inks 9101–9104. We have not yet evaluated this product but based on the information in the associated data sheets, it leverages the same chemical sintering process as NBSIJ–MU01 and should be compatible with the techniques we describe in this paper. Methode also supply a 'kit' containing a consumer-grade Epson ink-jet printer, 20ml of conductive inkjet ink and 40 sheets of coated substrate for US$900.

Selecting a suitable printer

We couple the silver nanoparticle ink with a commercial off-the-shelf desktop inkjet printer, thereby avoiding custom or expensive equipment. These printers typically deform piezoelectric material in the nozzle in order to deposit ink droplets on a paper substrate. We have focused on inkjet printers manufactured by Brother Co. because their nozzles tend to eject higher volumes of ink than alternative brands, which means that greater amounts of conductive ink can be deposited. The results presented in this paper are from a Brother DCP–J140w (Figure 1), chosen simply because it was the least expensive model available on Amazon.com when we purchased it in 2012! Silver ink can be loaded into the machine by filling empty refillable ink cartridges provided from a third party company. We used a small plastic syringe to do this, see Figure 2. Note the use of a disposable filter to keep any contaminants out of the print pipeline. Reuse of original ink cartridges is not recommended because residual ink may contaminate the silver nanoparticle ink and result in poor sintering. The prices of the printer and the empty cartridges were US$76.99 and US$8.99 respectively.

Desktop inkjet printers typically use at least four different colors (CMYK) to print a full color image. Compared to regular ink, it is necessary to print a relatively thick layer of ink to achieve high conductivity, so the ink should be loaded into all of the cartridge positions. In our experience with the Brother DCPJ140w, at least 10ml of ink is needed in each cartridge, perhaps 15ml in the larger black cartridge. Note that this model of printer doesn't have any electronic identification or level detection built into the cartridge itself, but instead appears to employ a relatively simple optical level detection mechanism. It should be noted some printers do not use the K cartridge at the same time as CMY cartridges.

[2]Prices may vary depending on the supplier and exchange rate, we are assuming US$1 = JP ¥100. International orders are available through Mitsubishi Imaging, Inc. [1].

Figure 2. Filling an empty cartridge with conductive silver ink using a plastic syringe and disposable filter. Note that the ink is dark brown before it sinters.

Choosing a substrate to print on

Inkjet printer paper is typically chemically coated to absorb the ink effectively and prevent smearing. This thin, porous coating plays an important role in the chemical sintering of the silver nanoparticle ink. In addition, surface roughness is also an important factor in establishing the nano-scale conductive structure on the surface.

Resin coated paper, transparent PET film and white PET film suitable for inkjet printing of chemically sintered silver nanoparticle ink are commercially available from companies such as Mitsubishi Paper Mill. However, we have also used glossy photo paper, such as Kodak Premium Photo Paper and Fujifilm Photo paper Kassai Pro.

We have also found a number of substrates designed for desktop inkjet printing which are *not* suitable for instant inkjet circuits. These include canvas cloths (Item 652–041, Office Depot), magnet sheets (Item 652–061, Office Depot), Iron-on Transfer Sheet (Item 327–537, Office Depot), Clear label seal (28791, A-One), and Clear Transfer seal (51112, A-One). With these substrates we found the sheet resistance of printed structures was in excess of 100 $k\Omega/\square$.

Software

No customized software is required to drive the printer although the settings of the printer driver should be configured for optimum performance. In short, the best conductivity is achieved when the settings are configured as shown in Table 1. The aim is essentially to as much ink as possible deposited on the paper because good conductivity relies on each 'dot' of ink merging with its neighbors to form a continuous conducting path. Note that in "photo" mode, the printer uses C, M and Y simultaneously to create black, which means more ink is used compared with the case when only K is used.

Any vector or pixel-based drawing software can be used as long as the conductive pattern is drawn in the color black. Figure 3 shows a printed circuit board for an Arduino, which illustrates two things: Firstly, it is straightforward to print Gerber format files which are commonly used for printed circuit boards. The second point is that transparent film can be

Paramter	Value
Media Type	Other Photo Paper
Print Quality	Best
Color Mode	Vivid
Color Enhancement	Enable
Color Density	+2
Improve Pattern Printing	Enable

Table 1. Brother DCP-J140w printer settings for optimal performance when using Mitsubishi NBSIJ-MU01 silver nanoparticle ink.

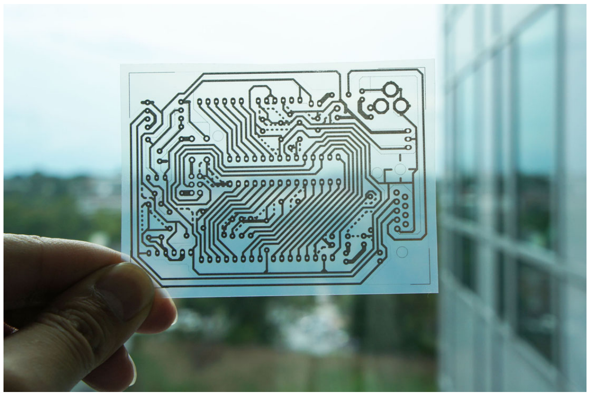


Figure 3. A single-sided wiring pattern for an Arduino was printed on a transparent sheet of coated PET film, directly from the Gerber photoplot.

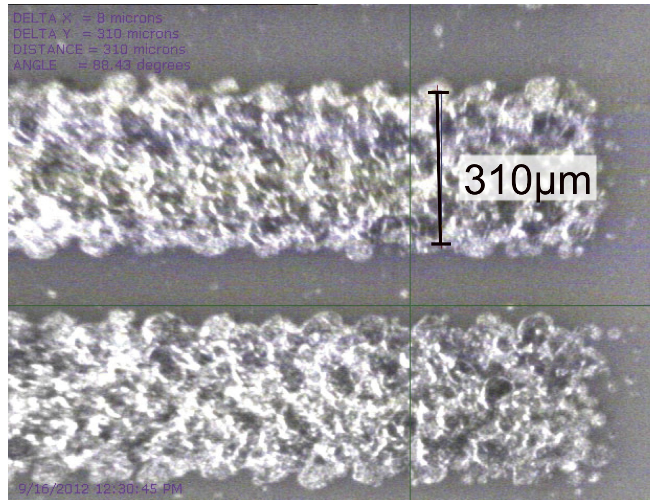
used as a substrate. Of course, in this case although the circuit board is flexible, components like the microcontroller are not, so it is not possible to make the entire board bendable. We will discuss methods for attaching components in a later section.

EVALUATION OF INSTANT INKJET CIRCUITS

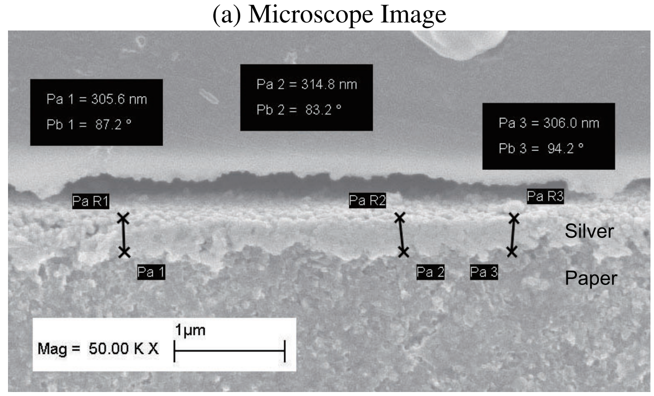
Visual inspection of a printed trace

Figure 4 (a) presents a microscope image of two parallel strip lines printed on Mitsubishi paper. Note that the small blobs in the image are groups composed of thousands of silver nanoparticles and polymers, and are not the silver particles themselves. Even though the surface is not smooth at the microscopic level, all the ink droplets coalesce together to form a solid conductive surface. The design width of the line was 250 μm. The actual line width expanded to 310 μm, however, due to the property of the ink and the discretization of going from a vector image to discrete drops in the printer driver. The actual size of a single silver nanoparticle is about 20 nm. Figure 4 (b) depicts a cross-section view of a printed silver pattern captured by a scanning electron microscope (SEM). The SEM image shows that the thickness of silver is around 300 nm.

To evaluate the performance of chemically sintered instant inkjet circuits, solid patterns with dimensions of 1.0 mm × 50 mm, 0.50 mm × 50 mm, and 0.25 mm × 50 mm were drawn on-screen using Adobe Illustrator CS6 and printed on resin coated paper. The sheet resistance of these patterns was calculated by measuring their resistance and using the formula $R_s = RL/W$ where R is the measured resistance in Ω, and



(a) Microscope Image



(b) Cross-sectional SEM Image

Figure 4. (a) Microscope image looking down onto two adjacent printed silver traces. Note that the printed pattern tends to expand by about 60 μm, here it is 310 μm wide. (b) A scanning electron microscope (SEM) image of a printed trace shows a cross-section view from which the thickness of the sintered trace can be measured at around 300nm.

W and L are the width and length of the pattern. The sheet resistance values immediately after printing on Mitsubishi paper and Kodak paper were 0.21 Ω/□ and 1.3 Ω/□, respectively. The sheet resistance values 10 hours later were 0.19 Ω/□ and 0.28 Ω/□, respectively. Figure 5 shows a plot of these results.

The effect of flexing

The changes in resistance that took place when a sheet was flexed are shown in Figure 6. The measurements were carried out by bending printed patterns around different diameter circular formers. For all tests the dimensions of the pattern were 5.0 mm × 174 mm. As can be seen in the figure, the sheet resistance increases as the bend radius decreases. This increase in resistance is attributed to cracking which occurs at the interface between individual nanoparticles due to the strain gradient caused by bending. If a printed pattern is bent too sharply, it suffers a non-reversible degradation in resistance. In our experiments the resistance increased up to a maximum of 34 Ω/□ when the pattern was wrapped around a toothpick. However, it's worth pointing out that this resistance was still lower than that of many conductive paints.

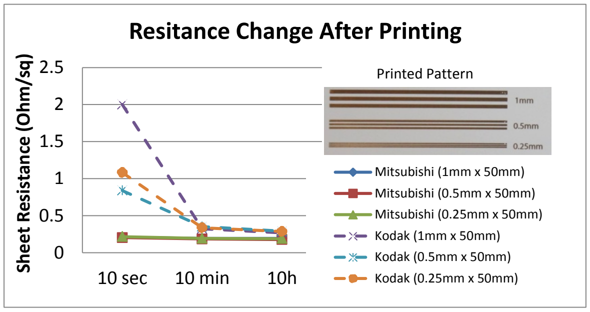


Figure 5. The ink instantly becomes highly conductive when Mitsubishi glossy paper is chosen. The final conductivity of Kodak Premium Photo paper was almost the same.

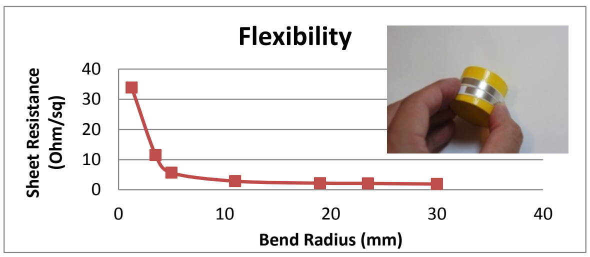


Figure 6. Increase in resistance is permissible for most applications wrapped around an object thicker than a pen.

Adding a laminate coating

We found that the resistance of printed traces increases by around 15% after 7 months. In our tests, the sheet resistance increased from 0.19 Ω/□ to 0.22 Ω/□ in this period. We believe this is due to oxidization of the silver nanoparticles.

One of the easiest approaches to prevent this oxidization is to coat the substrate with a thin plastic film. Commercially-available laminating machines designed for home and office use are sufficient for this purpose. We tested an 8 μm thick film from MICRONEX (EPS Co., Ltd.), the thinnest laminate we could readily purchase online. Using this film, it is possible to make the entire surface hydrophobic and to prevent air contact. It should be noted that coating of 8 μm laminate film doesn't significantly reduce the flexibility of the sample. No degradation in sheet resistance was observed following lamination in this way.

Increasing conductivity

Although the resistance achieved directly after printing is already acceptable for most applications, the sheet resistance value of an instant inkjet pattern is still around 4 times higher than that of a pure copper trace with the same width and thickness. In some applications, for example involving RF circuitry or very low power design, this could be an issue. For this reason we have explored methods to further reduce resistance.

The first approach we found useful is enhancing the chemical sintering by adding water, a known technique for accelerating the process [22]. By exposing the sample to a high humidity atmosphere (35 °C, 80%RH) for 10 minutes, the resistance was decreased by 4.8%. Note that this improvement is permanent, i.e. it is retained after the humidity is reduced to normal levels.

The second approach involves overprinting the pattern. Theoretically speaking, when the thickness of a conductive material is doubled, the resistance will be halved. In reality, we have found that resistance actually decreases to 60% after printing the same pattern twice. This is probably because chemical sintering is reinvigorated through the reintroduction of water contained in the ink. When the trace was printed once more (in total 3 layers), an additional resistance decrease was observed, this time to around 46% of the original value, i.e. a further 14% improvement. Unfortunately, the tray-based paper loading mechanisms which are very common in low-cost desktop inkjet printers are not good for accurate printing alignment. Misalignments of up to 0.5 mm typically occur when paper is loaded, so this technique is only practical for wider traces.

INKJET CIRCUITS IN UBICOMP APPLICATIONS

In this section, we describe how we think instant inkjet circuits can be exploited in a ubiquitous computing research environment. Picking up on some of the related work which we presented earlier, we have highlighted a number of techniques which are frequently used by UbiComp practitioners. For each of these we describe the fundamental principles of operation and then illustrate how instant inkjet printing could be used to assist implementation. In each case, the ability to cheaply and rapidly fabricate and iterate the printed circuitry is a key enabler. In some cases the flexibility of the resulting prototype is also critical.

Rapid prototyping electronic circuits

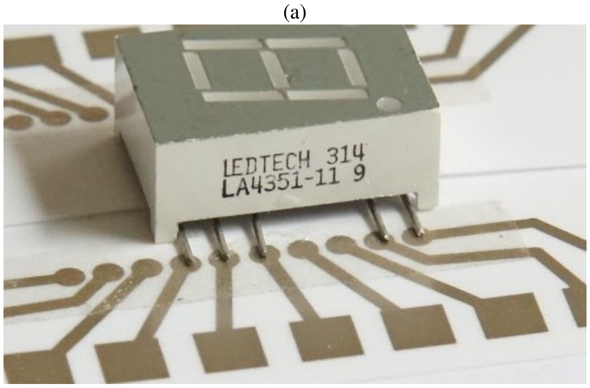
One of the most fundamental tasks in building UbiComp devices is constructing suitable electronic hardware. As discussed in the related work section, several electronics assembly options are available for prototyping, but these have various disadvantages. We are keen to leverage instant inkjet circuits for this purpose.

Unfortunately, conventional soldering techniques are not suitable for connecting components to inkjet circuits because solder typically melts at a much higher temperature (e.g. 180 °C) than is tolerated by the substrate coating essential to the chemical sintering process. In addition, the substrate itself may not be able to endure high temperatures. Low-temperature solder variants are available and these mitigate this issue, but soldering is still largely unsatisfactory.

Rather than soldering, in our experience silver conductive epoxy is the most robust way to connect wires and components. This is a two-part epoxy which is loaded with silver particles and which typically begins to harden 10 minutes after the two pastes are mixed. We used MG Chemicals 8331 epoxy. The conductivity increases as the epoxy cures, reaching a maximum after several hours at room temperature. By curing at 65 °C in an oven it is possible to shorten the time to just 15 minutes.

Conductive tapes are also very useful for prototyping with inkjet circuits. 3M provides a wide variety of such tapes;

(a)



(b) A pin and a pad is electrically connected but insulated from the adjacent pins due to anisotropic property of the adhesive tape.

Figure 7. Connecting components using a conductive double-sided adhesive tape.

we have found 3M Electrically Conductive Adhesive Transfer Tape 9703 to be the most useful tape for mounting electrical components onto inkjet circuits because of its anisotropic electrical conductivity. The tape is filled with conductive particles which allow interconnection between substrates through the adhesive thickness (the "Z-axis" of the tape). 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 fine-pitch electronic components to a substrate. Figure 7 shows different electrical components which are mounted in this way using clear conductive double-sided adhesive tape. The seven segment display in Figure 7 has 11 legs in total; each leg is connected to small pads printed on paper. Thanks to the anisotropic electrical conductivity of the tape, users simply need to align the pins on each component with the corresponding pads on the inkjet circuit. We have anecdotal evidence from research colleagues that self-adhesive transfer tape loses its adhesion after a period of days or weeks, but this had not been our experience. However, whilst we found the adhesive to be strong enough for prototyping when users need a mechanically stronger connection, the use of silver epoxy is suggested.

Using these techniques we have successfully built simple circuits which certainly match the sophistication of digital craft projects, as well as providing a useful basis for simple UbiComp applications. In terms of crafting, it is also worth noting that the resistance of the conductive threads and fibres commonly used is significantly higher than inkjet printed equivalents.

Inter-digitated capacitive touch sensing

Capacitive sensing has become an important way of detecting touch-based interaction between a user and all manner of digital devices. Using inkjet printing technology, we can fabricate uniquely-shaped capacitive sensing electrodes which are optimized for a particular application. We will review basic principles of capacitive sensing so that we can clearly explain our proposed approach.

Capacitance is defined as the ability of an electronic device to store electric charge. The simplest parallel-plate capacitor consists of two conductors separated by an insulator. The capacitance C of the parallel-plate capacitor is calculated as $C \approx \varepsilon A/d$. ε is permittivity of the insulator in Farads per meter, A is area of the plate in m^2 , and d is the distance between the plates in m. Permittivity is a measure of how the specific insulator used in the capacitor affects its ability to store charge.

Touch-sensitive consumer devices like laptops and smart phones contain a two-dimensional array of sensing electrodes, each of which forms one plate of a capacitor. Initially the parasitic capacitance measured at each electrode is very small. However, as a fingertip approaches the sensor element a change in capacitance can eventually be detected. A number of innovative touch sensing research projects in the literature such as DiamondTouch[7] and Touché [19] are based on this principle and instant inkjet printed electrodes are ideal for exploring this space further.

So-called inter-digitated sensors are formed from two electrode patterns with an 'interlocking' physical structure which is chosen in order to increase the inherent capacitance and maximize sensitivity to changes in permittivity (Figure 8). Thinking about the case total area of the capacitor is fixed, the increase rate of capacitance C with and without a high permittivity object is calculated as a as follows:

$$C_{increase\ rate} = \frac{C_{after} - C_{before}}{C_{before}} \quad (1)$$

$$= \frac{\left(\varepsilon_{air}\frac{1-S_{obj}}{d} + \varepsilon_{obj}\frac{S_{obj}}{d}\right) - \varepsilon_{air}\frac{1}{d}}{\varepsilon_{air}\frac{1}{d}} \quad (2)$$

$$= \frac{\varepsilon_{obj} - \varepsilon_{air}}{\varepsilon_{air}} S_{obj} \quad (3)$$

ε_{obj} and ε_{air} are permittivity of object and air respectively, and S_{obj} is proportion of the capacitor which is covered by the object when total area of the sensor is 1. d is distance between the sensor and the object. This equation indicates the capacitance change is proportional to the size the object occupies when difference of the permittivity of the object and air is large.

In order to explore the use of instant inkjet inter-digitated touch sensors, we fabricated a flexible sensing sticker that

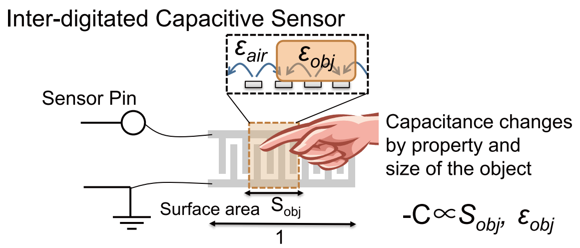


Figure 8. Operating principle of an inter-digitated capacitive sensor.

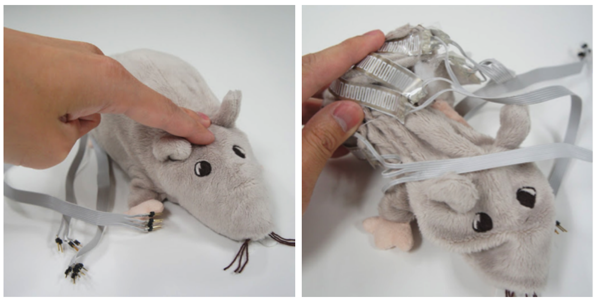


Figure 9. A plush toy instrumented with an instant inkjet printed capacitive sensor ribbon.

can be readily integrated with flat, curved or even flexible surfaces. The printed sensor electrode can be used to detect a slight change of permittivity near its surface; this signal can be easily read by off-the-shelf microcontrollers such as Arduino. In our prototype, we attached the sensing ribbon to the inside of the skin of a stuffed toy, see Figure 9. Since the capacitance of each strip can be read independently using multiple microcontroller I/O pins, it is possible to detect the exact touch location, causing the toy to react differently depending on the how the user touches it during interactions.

Capacitive sensing for liquid level detection

Figure 10 shows another example application based on a ribbon-shaped inter-digitated sensing sticker. A laminate-coated sensor strip is attached to the inside of a drinking glass. The flexibility of the ribbon allows it to fit to the curved surface of the glass. Its capacitance is measured using an Arduino nano and the Arudino CapSense Library. The graph in Figure 10 shows a very good correlation between measured capacitance and liquid level, and for comparison the printed sensor is much more accurate than the RFID-based system presented in [3]. Since the sensor ribbon is insulated by a laminate coating, it will not contaminate the liquid in the glass (or vice-versa). The manufacturing cost of one sensor ribbon is no more than a few cents while the Arduino-based capacitance reader costs a few tens of dollars.

Printed Antennas

An antenna is an electronic component that converts electrical energy into electromagnetic radiation in the form of radio waves and vice-versa. The simplest antennas consist of only an arrangement of metallic conductors, and in this case the conductivity, permittivity and shape of the antenna has a huge bearing on its performance.

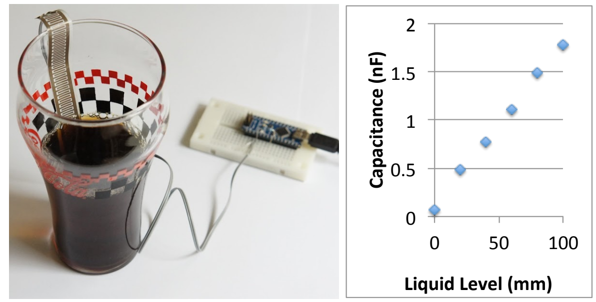


Figure 10. A laminate-coated inter-digitated capacitive ribbon is attached inside a drinking glass. The ribbon is connected to the digital I/O of Arduino nano in order to measure the capacitance which is proportional to the liquid level

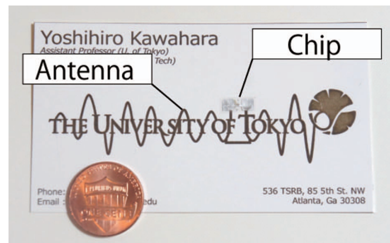


Figure 11. University logo is modified as 915MHz UHF band antenna. RFID chip is attached using conductive epoxy.

Figure 12. Performance of custom printed RFID tag.

A 915MHz band dipole antenna was designed based on a university logo using the CST Studio microwave simulator. The dimensions of the antenna are such that it fits onto a standard sized business card. The antenna impedance was matched to that of a standard RFID chip to support direct attachment to the antenna terminals using conductive epoxy. Figure 11 shows the final antenna design, which is a combination of the university logo and a functional UHF folded dipole antenna. Figure 12 shows the performance of the assembled RFID tag, which was comparable to that of a commercial low-profile UHF RFID tags. This result demonstrates that our instant inkjet printing process is suitable for prototyping RF structures such as antennas.

Time domain reflectometry

Wimmer et al. did not suggest the use of inkjet printing their work on time domain reflectrometry for sensing interaction [21], but we have successfully implemented this technique using an inkjet printed transmission line, see Figure 13. We used a Hilbert curve as the basis of the stripline pair which makes up the transmission line. This is a fractal space-filling curve that gives a fairly good mapping between 1D and 2D space that preserves locality, which means that the pattern offers consistent touch resolution in the x and y directions.

DISCUSSION

Additional practical issues

Throughout the course of this work we have been pleasantly surprised how well the inkjet process has worked. Of course, a number of issues have come to light. As already mentioned,

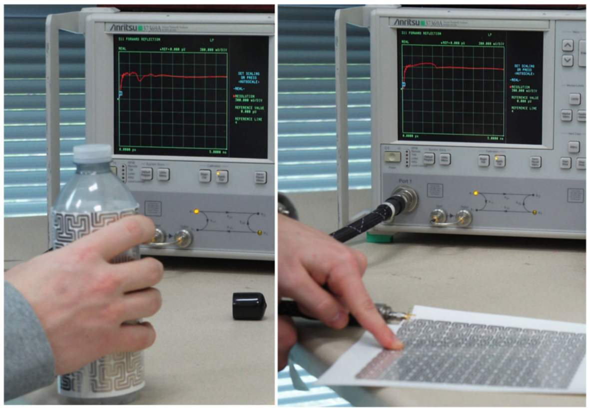


Figure 13. Hilbert pattern; 200 mm × 200mm. Result of TDR changes depending on how the surface is touched (left) and position of pointed (right).

the emergence of conductivity is heavily dependent on surface coating and smoothness. The printed pattern is flexible but not stretchable – even if the underlying substrate is stretchable the microscopic structures inside the silver traces would likely be broken and conductivity lost. Having said this, we have so far been pleasantly surprised about the durability of the circuits we have prototyped.

Users should observe the health and safety guidelines described in the materials safety data sheets supplied with the ink, especially when loading an empty cartridge. Although NBSIJ–MU01 is water-based and may be washed away with soap and water before it dries, users should wear rubber gloves and goggles to protect eyes and hands. The ink dries instantly when it is printed onto coated paper so there is no need to treat the printed pattern. In general, silver itself is not toxic and is not classified as a harmful metal so when it's dry we are not aware of any special precautions which are necessary. Since the size of the silver nanoparticles is larger than color particles in standard ink, the nozzle can become clogged. In most cases we found that the built-in printer cleaning operation clears the clogging if run a few times.

Future research directions

We are excited to explore a number of future directions for this work. One important issue to address is the single-layer nature of inkjet printed circuits, which is quite limiting in comparison to multi-layer PCBs. We would like to explore the combination of inkjet printing and laser cutting to create sets of origami-style circuits which interconnect with each other. This would allow the creation of 3D prototypes with embedded conductors, as proposed in [18].

In a similar way, circuits with cut-outs, folds and multiple elements could be used to implement a wider range of sensing devices – such as push switches, sliders, weighted orientation sensors and so on. Not only could cheap sensors like this be useful in a UbiComp setting, but they could also be valuable for education. Using instant inkjet circuits in the classroom it would be possible to introduce students to basic electronics principles very cheaply, and coupled with the use of anisotropic self-adhesive tape a range of electronic components could be used to augment the experience. Ultimately it might be possible to adopt a solderless modular electronics platform like .NET Gadgeteer [11] to use an inkjet printed substrate for interconnect instead of individual cables. This would support a quite sophisticated learning experience more cheaply and easily than is currently possible.

Throughout this paper, all the patterns printed have been digitally created, but it is of course possible to hand-draw circuits with a regular marker pen and then transform them into conductive circuits using the printer in its 'photocopier' mode. We have done some initial tests which show this works. It opens up yet more applications in the education domain, and is very appealing for digital crafting and beyond[15, 10, 17].

One final area we are excited to explore is the creation of more sophisticated prototypes by loading different materials into the different inkjet cartridges. This might allow us to vary the resistance of printed structures which could form the basis for printed resistive sensors. Other printable materials under active development are targeting ink-jettable transistors, organic LEDs and even batteries [13], and whilst these currently still require very controlled laboratory conditions, we hope that in time they will also become more accessible in the same way that nanoparticle silver ink has. We also want to explore the use of printed polyester insulating layers and may eventually support inkjet printed sensors using with grapheme and carbon nano-tubes.

CONCLUSIONS

In this paper we presented an approach to inkjet printing flexible circuits in the laboratory which has only recently become possible. In particular, a chemical sintering process means that it is now possible to use inexpensive off-the-shelf inkjet printers, making the technology very accessible to practitioners. There is no need for a time-consuming thermal sintering step, making the process almost instantaneous. The fundamental enabler is a range of chemically-sintered silver nanoparticle inks available from several suppliers.

We have described in detail the materials, equipment and techniques which we have found to be effective. For example, the use of anisotropic electrically conductive adhesive tape for mounting components onto inkjet circuits in some senses matches the 'solder-less' characteristic of breadboard circuits, in that it is incredibly quick, easy even for non-experts, and allows components to be removed and subsequently re-used.

In addition to breadboard and PCB replacements, the properties of our instant inkjet circuits allow us to support a variety of additional applications within the broader domain of ubiquitous computing. In addition to providing enough practical details for others to replicate these techniques without repeating the mistakes we made along the way, the specific contributions we present in this paper are:

1. a characterization of printed trace sheet resistance and how this changes as the traces dry, bend and age;
2. measurements of the beneficial effects of humidity and over-printing on sheet resistance;

3. a discussion of techniques for attaching electronic components to printed traces;
4. an illustration of capacitive sensing using printed electrodes for touch, multi-touch and liquid level detection;
5. a demonstration of using printed UHF structures such as RFID tag antennas and transmission lines; and
6. a number of directions for future work.

We hope that others working in the field of ubiquitous computing will be excited to look for opportunities to leverage instant inkjet printing for the projects they are working on, and will be inspired to take the ideas we presented in this paper in new and exciting directions.

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REFERENCES
1. Mitsubishi imaging, inc. http://www.mitsubishiimaging.com/digital-imaging-diamond-jet-NANOINK.html.
2. Bare paint. http://www.bareconductive.com/.
3. Bhattacharyya, R., Floerkemeier, C., and Sarma, S. RFID tag antenna based sensing: Does your beverage glass need a refill? In *Proc. of IEEE RFID 2010*, IEEE (Apr. 2010), 126–133.
4. Bhattacharyya, R., Floerkemeier, C., and Sarma, S. Rfid tag antenna based temperature sensing. In *Proc. of IEEE RFID 2010*, IEEE (2010), 8–15.
5. Coelho, M., Hall, L., Berzowska, J., and Maes, P. Pulp-based computing: a framework for building computers out of paper. In *Proc. of CHI EA '09*, ACM Press (Apr. 2009), 3527–3528.
6. Circuitworks conductive pen. http://www.chemtronics.com/products/product.asp?r=1&m=2&id=7.
7. Dietz, P., and Leigh, D. DiamondTouch: A Multi-User Touch Technology. In *Proc. of UIST '01*, ACM Press (Nov. 2001), 219–226.
8. Dimatix Material Printer DMP-2831. http://www.fujifilmusa.com/products/industrial_inkjet_printheads/deposition-products/dmp-2800/.
9. Ford, M. Can the 'silver bullet' of printing revolutionize electronics? Digital Biz, CNN, December 10th, 2009., http://www.cnn.com/2009/TECH/12/09/electronics.printer.xerox/.
10. Gong, N.-W., Hodges, S., and Paradiso, J. A. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. In *Proc. of UbiComp '11*, ACM Press (Sept. 2011), 45–54.
11. Hodges, S., Scott, J., Sentance, S., Miller, C., Villar, N., Schwiderski-Grosche, S., Hammil, K., and Johnston, S. .net gadgeteer: a new platform for k-12 computer science education. In *SIGCSE* (2013), 391–396.
12. Holman, D., and Vertegaal, R. TactileTape: low-cost touch sensing on curved surfaces. In *Adjunct Proc. of UIST '11*, ACM Press (Oct. 2011), 17–18.
13. Jablonski, C. Printable batteries. ZDNet, July 17th, 2009., http://www.zdnet.com/blog/emergingtech/printable-batteries/1648.
14. LPKF Promat Series. http://www.lpkf.com/.
15. Olberding, S., Gong, N.-W., Tiab, J., Paradiso, J. A., and Steimle, J. A cuttable multi-touch sensor. In *Proc. UIST'2013*, ACM Press (Oct. 2013).
16. Perner-Wilson, H., Buechley, L., and Satomi, M. Handcrafting textile interfaces from a kit-of-no-parts. In *Proc. of TEI '11*, ACM Press (Jan. 2011), 61–68.
17. Qi, J., and Buechley, L. Electronic popables: exploring paper-based computing through an interactive pop-up book. In *Proc. of TEI '10*, ACM Press (Jan. 2010), 121–128.
18. Sarik, J., Butler, A., Villar, N., Scott, J., and Hodges, S. Combining 3D printing and printable electronics. In *Proc. of TEI '12 Works in Progress*, ACM Press (Feb. 2012), 1–5.
19. Sato, M., Poupyrev, I., and Harrison, C. Touché: enhancing touch interaction on humans, screens, liquids, and everyday objects. In *Proc. of CHI '12*, ACM Press (May 2012), 483–492.
20. Savage, V., Zhang, X., and Hartmann, B. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. *Proc. of UIST '12* (2012), 579–588.
21. Wimmer, R., and Baudisch, P. Modular and deformable touch-sensitive surfaces based on time domain reflectometry. In *Proc. of UIST '11*, ACM Press (Oct. 2011), 517–526.
22. Yoshiki, T., Shino, S., and Kobayashi, K. Process for preparing conductive material, United States Patent, US 8012676 B2, 2011.