Circuit Stickers: Peel-and-Stick Construction of Interactive Electronic Prototypes

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ABSTRACT

We present a novel approach to the construction of electronic prototypes which can support a variety of interactive devices. Our technique, which we call *circuit stickers*, involves adhering physical interface elements such as LEDs, sounders, buttons and sensors onto a cheap and easy-to-make substrate which provides electrical connectivity. This assembly may include control electronics and a battery for standalone operation, or it can be interfaced to a microcontroller or PC. In this paper we illustrate different points in the design space and demonstrate the technical feasibility of our approach. We have found circuit stickers to be versatile and low-cost, supporting quick and easy construction of physically flexible interactive prototypes. Building extra copies of a device is straightforward. We believe this technology has potential for design exploration, research prototyping, education and for hobbyist projects.

Author Keywords

Conductive inkjet; silver ink; rapid prototyping; physical computing; solderless electronics; tangible interfaces.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

In recent years there has been an explosion in the availability and use of electronic prototyping platforms in a range of disciplines such as design exploration, technology education, research prototyping and within the hobbyist communities [1,2,10,13]. These tools typically comprise electronic hardware modules which are readily connected together to produce compact and robust assemblies. However, traditional techniques like hand soldering and the use of solderless breadboards still have the edge for many applications and are therefore frequently used too.

In this paper we present a new approach to prototyping with electronics which we call *circuit stickers*, see Figure 1. In our scheme, the hardware building blocks for constructing a device are simple elements in the form of small printed circuit board (PCBs). These are connected together physically and electrically to form a working prototype by sticking them onto a cheap and easy-to-make substrate. A battery can be included for standalone operation, or the resulting assembly can be interfaced to a microcontroller or a PC.

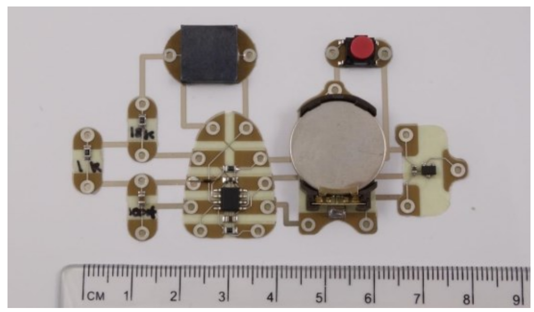

Figure 1: An example circuit sticker design. The stickers needed for a coin-cell powered musical toy are stuck to a sheet of paper which has been inkjet printed with silver conductors.

Whilst our technique is not a panacea, it provides a useful alternative to established approaches. We believe it is particularly well-suited to building reasonably compact and robust interactive devices. It is simple to use, versatile, easy to replicate and results in physically flexible prototypes.

In the remainder of this paper we describe the design and use of circuit stickers. Following a discussion of related work, we describe the concept in more detail and outline some of the sticker elements we have built so far. The conductive substrate which the circuits are attached to may be hand-crafted or designed digitally; we describe the processes we have used in our research to date. We then present different prototypes built using circuit stickers to validate the potential of our approach. We imagine applications in several domains such as design exploration, research prototyping, education and home use. We do not provide a formal evaluation but rather aim to establish the concept, explore the possibilities it affords and demonstrate its potential. We conclude with a number of areas of future work.

RELATED WORKS

Electronics Prototyping

Users who are prototyping electronic circuits have several construction options. A common approach is the use of

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processor boards like Arduino [1] in conjunction with discrete wires, components and breadboards. The use of wires allows flexibility when positioning interface elements like LEDs and switches and the resulting circuits can readily be modified to explore different designs or debug problems. However, they can be relatively cumbersome and fragile, and the wiring process can be tedious and error-prone.

More modular platforms address some of the issues associated with using discrete wires and components. LittleBits [2], VooDooIO [12], Phidgets [6] and .NET Gadgeteer [13] use higher level abstractions and custom hardware to simplify assembly and reduce the iteration cycle. This added convenience comes at a tradeoff, however – the size and layout of the resulting circuit is constrained, and the range of components and possible configurations may be limited.

Quick-turnaround, low-volume PCB manufacturing is another option for constructing prototypes. PCBs support fine-grained positioning of components and bypass the need to manually wire them up, enabling complex yet compact designs which are physically robust. However, assembling and modifying a PCB-based prototype can be difficult.

Circuit stickers combine positive elements from the above techniques, offering a prototyping "sweet spot" for some applications. Circuit stickers are faster and cheaper to use than PCBs, more reliable and compact than breadboards, and more versatile than higher-level modular systems. They can also make it easier to replicate, evaluate and ultimately extend prior work in this area including the above systems. The aim of this paper is to illustrate what is possible with this easy-to-use technique and to facilitate further research.

Producing and Attaching to Conductive Substrates

Circuit stickers rely on a conductive substrate to provide electrical interconnection. This substrate can be created by hand using conductive ink and paint (e.g. http://electroninks.com and http://bareconductive.com), or can be designed on a computer and then printed. We have explored both, but in this paper we primarily focus on the latter. In particular, we build on our previously published technique of Instant Inkjet printing [9] which produces conductive silver traces with a domestic inkjet printer. The high spatial resolution and low resistance of inkjet-printed traces enables end-users to easily and rapidly output complex patterns on a thin paper or plastic substrate, which is ideal for connecting and powering circuit sticker elements.

Conductive epoxy has previously been used to attach components to a flexible substrate [6], and in [9] we suggested the use of anisotropic electrically conductive adhesive transfer tape (ECATT) [4]. ECATT is essentially double-sided conductive tape that only conducts from one side to the other and not across either surface, and it is much easier to use than epoxy. Unfortunately it results in electrically and mechanically fragile bonds when the contact area is small, which is the case for most electronic components. Circuit stickers work around these problems by mounting electronic components onto intermediate PCB carriers. This simple step is a key contribution of this work because it increases the substrate contact area and therefore makes the use of ECATT practical for a wide range of applications.

Flexible Circuits

Physically flexible circuits have been explored by many researchers. Buechley [3] developed several solder-less techniques for constructing working electronic circuits on paper – enabling games, interactive paintings and sculptures. Similarly, Freed et al. [5] used conductive tapes to build a kit of flexible sticky circuit pieces. Mellis et al. [10] presented ways to construct interactive artifacts using conductive ink, paper, off-the-shelf electronic components, and hardware and software tools. Savage et al. [11] demonstrated a new way to design and fabricate flexible touch sensors.

Circuit stickers, by virtue of their flexible substrate and conductive adhesive offer another point in the design space. They can be combined with all of these existing systems to improve ease of use or extend the design possibilities.

CIRCUIT STICKER IMPLEMENTATION DETAILS

Our initial approach was to create stickers encapsulating very basic circuit elements, such as individual components and simple sub-circuits. We designed a number of these to illustrate the concept and gain experience with simple interactive designs. Our *generic stickers* include a single electronic component footprint such as an 0805 passive or SOT-23 transistor. These are ideal for trying out new ideas because a wide range of electronic components can be soldered directly to them. More specific *sub-circuit stickers* which house a small group of components can be designed when a particular electronic device needs to be adopted, e.g. an analog accelerometer with decoupling and filtering or a simple microcontroller with support circuitry. Some of our initial circuit stickers are shown in Figure 2.

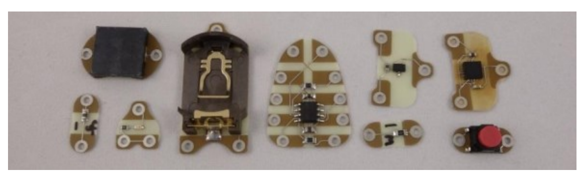

Figure 2: Circuit stickers. From left: generic 0805, piezo sounder, LED, coin-cell battery holder, 555 timer, hall-effect sensor, accelerometer, push button.

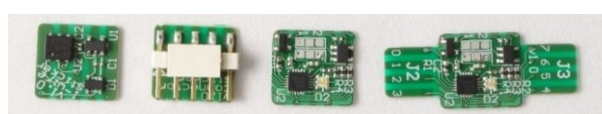

Figure 3: One-wire and I2C bus-based circuit stickers. The touch sensor (right) has extra connections for touch electrodes.

Circuit stickers are not a panacea. A knowledge of electronics is required and there is scope for human error when using them. Circuits with more than 10-15 stickers can become cumbersome. To mitigate these shortcomings we have also developed some *bus-based sticker* designs. In this case the stickers are used primarily for input and output, with computation, storage and communications offloaded to a conventional microcontroller or a PC. To explore this pattern of use, we created a bus-based sticker design, where several parallel traces are inkjet printed on the substrate to form a 1-wire or I2C bus between multiple stickers. The bus needs to carry power as well as data and the stickers have corresponding interfaces. See Figure 3.

All of our sticker prototypes adhere to some basic design rules determined through experimentation. The contact pads on the bottom of a sticker are typically 10-20mm^2 with a minimum dimension of 1.5mm and at least 1mm between adjacent pads. This ensures good electrical connection to the substrate but avoids short-circuits. We also ensured a total sticker size of at least 50mm^2 for mechanical stability. We have used two different PCB materials, FR4 and the more flexible Kapton, both ~0.15mm thick. To assemble, we either apply ECATT to the underside of the PCB and then trim off the excess material, or we apply a piece of ECATT to the substrate and then affix a bare sticker.

DIGITAL DESIGN TOOLS FOR CIRCUIT STICKERS

Instant inkjet circuit designs can be created using any software with a ‘printable’ output, e.g. Adobe Illustrator or Microsoft PowerPoint. However, manually creating a design which is compatible with the underside of each sticker and which also provides the necessary interconnections from scratch can be time consuming and error prone. To give a flavor of what is required, Figure 4 shows an example audio-frequency oscillator connected to a piezo sounder.

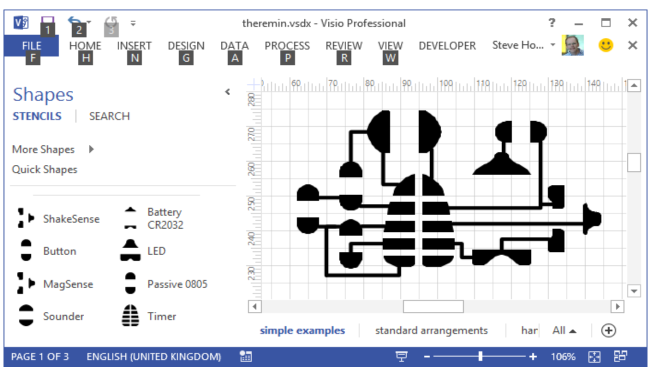

Figure 4: Using Visio to lay out a sticker circuit design.

To support the design process we built custom extensions to Microsoft Visio. We used the ‘stencil’ feature of Visio to define shapes which match the underside of each sticker circuit. The pads which make up these stencils are easily interconnected using the standard Visio ‘connector’ object.

A library of “pre-wired” common circuit sticker configurations was created to support re-use of previously developed and tested circuitry. This simplifies the creation of new designs. In addition, we used custom automation in Visio to allow it to automatically wire-up bus-based stencils. We use a simple algorithm which snakes the bus across the page, passing through each sticker on the bus (see Figure 7).

It is also possible to use standard PCB design tools like Eagle and Altium to design circuit sticker substrates. These have the necessary design rules built in and are much more powerful than our Visio extension, with interactive routing capabilities, trace impedance analysis etc. However, they also have a much higher learning curve.

CONSTRUCTING INTERACTIVE PROTOTYPES

To gauge the validity of our design decisions, we evaluated four different sticker circuit applications, each illustrating a different point in the design space. We hope that these will further explain our technique and how it can be used.

Simple lighting effects

Our earliest experiences with circuit stickers involved simple LED-based circuits built from substrates hand-crafted using conductive ink, self-adhesive copper tape, conductive threads and fabrics. These largely aesthetic designs (see Figure 5) were useful for validating the circuit sticker concept and refining our design rules.

A self-contained, creative musical toy

As a next step, we constructed a simple circuit using 8 different stickers. The center of the design was a 555 timer IC driving a piezo to create a noise-making toy. We incorporated a Hall effect sensor so that a magnet could be used to change the frequency of the ‘note’ being played. A coin cell powered the device via a push-button. See Figure 1.

Experimenting with gestural input

Our third example illustrates how circuit stickers can be combined with traditional electronics prototyping, by instrumenting a glove to sense the relative movement of the wearer’s fingers. For this, we designed and printed a flexible circuit and trimmed it to match the shape of the glove. We placed accelerometer stickers at the fingertips and applied a ‘connector sticker’ to allow the circuit to be hooked up to an external microcontroller. A .NET Gadgeteer [4] system was used to create a microcontroller-based display and logger for the accelerometer values. See Figure 6.

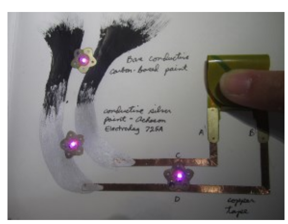

Figure 5: Mixed media.

Figure 6: Glove sensor.

Prototyping touch-based interfaces using an I2C bus

Instant inkjet printing is a natural fit for experimenting with touch sensing electrodes. To facilitate this, we built a ‘touch sensor sticker’ which connects a Freescale MRP121 I2C touch sensor IC to 8 printed electrodes in addition to the I2C bus (see Figure 3). The sticker also has a multi-color LED. We connected four of these across a sheet of A4 paper to wire the bus to a Gadgeteer I2C bus master programmed to light LEDs based on touch interactions. This prototype is shown in Figure 7.

DISCUSSION AND FUTURE WORK

Performance

In our experience circuit stickers are pretty easy to work with. As long as care is taken to ensure correct alignment, applying them is quick, easy and natural. They show good mechanical and electrical robustness; we have circuits that work well several months after being built. Stickers may be re-used by removing them carefully and cleaning the underside (we use "Sticky stuff remover" by "De-Solv-it".)

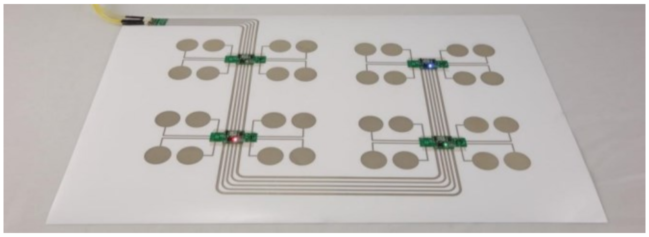

Figure 7: I2C bus-based design with distributed touch sensors and color LEDs. An I2C bus master connected by the yellow wires (top left) polls the touch sensors and controls the LEDs.

The sheet resistance of the Instant Inkjet traces introduces a measurable voltage drop, but for the circuits we constructed running an I2C bus at 100kbps was not an issue. However, it could be problematic for long traces or high currents. A solution for reducing resistive losses that we have successfully prototyped is to use a higher bus voltage in conjunction with a DC-DC converter on each sticker.

Further Aspects of Design

We would like to combine graphical elements using inkjet over-printing, and use laser cutting to support visually and functionally richer designs. We would also like to see how the stickers interface with other substrates, especially when cut, bent and folded into different configurations.

Other Application Areas

We have started exploring the use of circuit stickers in applications beyond creative design exploration and functional prototyping. For example, our approach could be a useful tool in education, encouraging a computational thinking mindset and helping students develop a better intuition of how electronic devices work. We imagine conductive worksheets which are used in conjunction with a class kit of circuit stickers. Basic stickers could be cheap enough for students to permanently keep working circuits.

Encouraging adoption

We would like others to build on our work. We have put design resources relating to our work online at http://research.microsoft.com/circuitstickers. In addition, at the time of writing, a basic range of open-source stickers including LEDs of different colours, specific controllers for these and a simple microcontroller are available to purchase at http://chibitronics.com. A new manufacturing technique developed by Andrew "bunnie" Huang allows kapton-based stickers to be supplied with ECATT pre-applied, making them easier to use. In addition to hobbyists and educators, we also imagine applications in design studio and research lab settings and are excited to explore these in future work.

CONCLUSION

By building and evaluating a number of different prototypes, we have demonstrated that circuit stickers can provide a practical alternative to traditional breadboarding and custom PCBs. When used in conjunction with the growing number of conductive printing technologies, circuit stickers support quick, versatile and easy electronics prototyping like breadboards, but they result in more compact and robust prototypes. Like PCBs, they are relatively easy to clone should more be needed, but they are much cheaper and quicker to make and naturally provide physical flexibility. Although PCBs can support more dense, sophisticated and durable prototypes, we believe that circuit stickers may have a useful role when these are not key considerations.

Our ultimate goal is to extend the tools and processes available for designing interactive prototypes. As we do this we hope to inform other practitioners working in this area by sharing our ideas and experiences in enough detail to enable them to adopt and adapt our work in new ways.

REFERENCES

1. Arduino. http://www.arduino.cc.
2. Ayah Bdeir. Electronics as material: littleBits. In *Proc of TEI '09*, pp. 397-400.
3. Buechley, L. et al. "Paints, Paper, and Programs: First Steps Toward the Computational Sketchbook" In *Proc. of TEI '09*, pp. 9-12.
4. 3M Electrically conductive adhesive transfer tape.
5. Freed, N. et al. Sticking together: handcrafting personalized communication interfaces. In *Proc IDC '11.*
6. Gong, N.-W.et al. Leveraging conductive inkjet technology to build a scalable and versatile surface for ubiquitous sensing. In *Proc of UbiComp '11*, pp. 45-54.
7. Greenberg, S., & Fitchett, C. Phidgets: Easy development of physical interfaces through physical widgets. In *Proc. of UIST '01*, ACM, 209-218.
8. Hartmann, B., Reflective physical prototyping through integrated design, test and analysis. In *Proc. UIST '06*.
9. Kawahara, Y et al., Instant Inkjet Circuits: Lab-based Inkjet Printing to Support Rapid Prototyping of UbiComp Devices. In *Proc of UbiComp '13*.
10. Mellis, D. A. et al. Microcontrollers as material: crafting circuits with paper, conductive ink, electronic components, and an "untoolkit". In *Proc of TEI '13*, pp. 83-90.
11. Savage, V. et al. Midas: fabricating custom capacitive touch sensors to prototype interactive objects. *Proc. of UIST '12*, 579–588.
12. Villar, N. & Gellersen, H. A malleable control structure for softwired user interfaces. In *Proc. of TEI '07.*
13. Villar, N. et al. .NET Gadgeteer: A Platform for Custom Devices. In *Proc. of Pervasive '12*, pp. 216-233.