

Pulp Nonfiction: Low-Cost Touch Tracking for Paper

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ABSTRACT

Paper continues to be a versatile and indispensable material in the 21st century. Of course, paper is a passive medium with no inherent interactivity, precluding us from computationally-enhancing a wide variety of paper-based activities. In this work, we present a new technical approach for bringing the digital and paper worlds closer together, by enabling paper to track finger input and also drawn input with writing implements. Importantly, for paper to still be considered paper, our method had to be very low cost. This necessitated research into materials, fabrication methods and sensing techniques. We describe the outcome of our investigations and show that our method can be sufficiently low-cost and accurate to enable new interactive opportunities with this pervasive and venerable material.

Author Keywords

Paper; Touch tracking; Multi-touch; Pen tracking; Electric Field Tomography; Input; Interaction Techniques.

ACM Classification Keywords

H.5.2. [User interfaces] – Input devices and strategies.

INTRODUCTION

Despite the ubiquity of computers, paper still occupies a central role in our everyday lives [5,30]. It is used in a dizzying array of products, from newspapers and calendars, board games and food packaging, to notepads and post-it notes. Indeed, paper is a convenient, low-cost, high-contrast and durable means to transport and view information. It also has enviable social, practical and aesthetic qualities that make it a popular and rapid means for writing text and drawing figures [30,66]. Despite much prognostication starting in the 1970's about a "paper-less future" [8,30,55], global paper consumption has instead continued to grow in lockstep with adoption of information and computing technologies [46,55,61].

Of course, unlike dynamic computing technologies, paper is static. Although we can read from and write on paper, it is not truly interactive – the paper is simply a passive medium.

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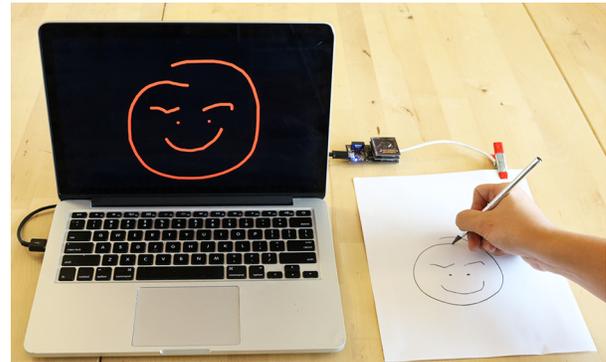


Figure 1. Our touch-sensing paper can track fingers and writing implements, allowing drawn and written content to be digitized and computationally enhanced.

In response, many projects have sought to *superimpose* computational capabilities, for example, facilitating information retrieval (e.g., barcodes, QRcodes [69], RFID tags [4,32]), enhancing paper-based experiences (e.g., augmented reality with printed ARtags [49]), and digitizing pen input [3]. In these systems, the “smarts” are contained in an external object (e.g., optical pen, RFID reader, barcode scanner, camera), but the paper itself is passive.

A second, more involved option is to *imbue* paper with sensing capabilities, typically touch sensing. This is most frequently achieved by instrumenting paper with conductive traces (e.g., copper stickers/tape [26,53], printed inks [2,10,20]) to enable capacitive touch-sensing elements, such as buttons and sliders (see e.g., [6,16,28,41,42]). Such methods generally cannot support continuous touch tracking across the entire surface of a sheet of paper, and instead must be designed in accordance with printed content (i.e., a fixed design). Additionally, most of these methods are targeted for one-off DIY or end user applications, and are generally impractical for mass production, undermining one of the key qualities of paper's success: cost so low it can be crumpled up and thrown away after a single use.

In this work, we explore a new approach to enable fully continuous touch tracking on paper at low cost, opening new opportunities. Our input method can support both fingers and writing implements, such as pens, pencils and brushes. In the extremely small volumes that we created for this project, individual sheets were created for little as 30 cents, not including our reusable sensing board. Although we do not see this immediately supplanting more traditional, externally sensed methods (e.g., Anoto pens [3]) – as these are far more practical in the short term – we do be-

lieve that our work significantly advances the feasibility of low-cost, interactive, paper-based experiences, especially those that are single use.

As we will discuss in greater detail, we achieve this tracking capability by coating paper, on one side (or sandwiched between two sheets), with a uniform, low-cost conductive layer. This could be applied en masse at the mill, before paper is cut from bulk rolls into e.g., notepad stock. To this layer, we add conductive traces connecting to different points on the periphery, which could be applied through any number of printing (e.g., offset printing, silk-screening) or mechanical processes (e.g., stamping, die-cutting). We then employ electric field tomography to localize touch inputs, which capacitively couple to our paper. We previously explored this general sensing approach in *Electrick* [72] for surfaces (e.g., tables, walls) and objects (e.g., toys, controllers). Paper is uniquely single use, and therefore must be mass produced at extremely low cost. This required innovation in our touch tracking pipeline, materials, fabrication processes, and writing implements.

RELATED WORK

We now review previous efforts to bring interactivity to paper, both via external and internal means. We also include a focused discussion relating to our technical approach.

Externally-Sensed Augmented Paper

Researchers have long sought to bring interactivity to paper. The most immediate way to track fingers and pens on papers is to use cameras in concert with computer vision. *DigitalDesk* [67] is perhaps the earliest effort in this domain, which used an overhead camera (and projector) to track finger and pen input for a variety of synergistic paper-computer interactions. *PaperWindows* [25] also used an overhead camera, which tracked an infrared-marker-tagged sheet of paper, enabling a series of paper gestures, such as bending a corner. Later, Lee et al. [31], Gallant et al. [17], and Steimle et al. [59] used camera setups to explore bending interactions and “paper-like” input.

Research has also considered mobile use contexts. For example, *PACER* [34] and *HOT PAPER* [14] utilized smartphone cameras to recognize documents and offered a suite of phone-based annotation tools. *FingerReader* [56] and *EyeRing* [40] used finger-worn cameras chiefly to assist visually impaired users with text and document recognition. *MagicFinger* [69], another camera-augmented ring system, could recognize printed codes on paper to trigger interactive functionality. It is also possible to integrate a camera into a stylus, and seen in the commercial *Anoto Pen* [3]. By using a proprietary dot pattern printed onto paper, *Anoto pens* can identify sheets of paper and localize their position on it. This technology has been widely used in digital paper research [21,34,35], including augmented note-taking systems [70], proof editing [65] and content linking [36].

Finally, it is also possible to overlay paper onto a reusable sensing panel. For example, *The Audio Notebook* [60] and *Wacom’s Bamboo Slate Smartpad* [64] can track pen

strokes on standard paper using an underlying digitizer. Similarly, *WonderLens* [33] used an underlying grid of Hall effect sensors to track tangibles on paper. Additionally, RFID tags can be attached so that sheets of paper can be identified with external readers [4,32].

Instrumented Paper

There is also a substantive literature on sensing fabrics [23,45, 50], as well as thin and flexible touch sensing technologies [43,51,52,68]. Although offering touch tracking in a flexible, sheet form factor, these research efforts were not attempting to augment traditional paper. Projects that did consider paper-like interactions sought to replace paper with a new, enhanced and reusable form, rather than augment the conventional (and disposable) pulp variety. For example, *DisplayStacks* [18] used E-Ink displays with integrated bend, location and orientation sensors, while *PyzoFlex* [51] used a patterned piezoelectric foil on a plastic substrate.

Closer to our work are methods that directly imbue conventional paper with interactive capabilities. Early among these efforts is *BOXES* [26], which demonstrated interactive cardboard interfaces made from “thumbtacks, tin foil and masking tape”. *Midas* [53] significantly extended this functionally by using a vinyl cutter in concert with custom design software to create DIY stick-able copper traces that could be overlaid onto objects, including paper, enabling capacitive buttons, sliders, and even 2D tracking.

The availability of flexible, conductive inks [2,10,20] has further enabled explorations in this space. For example, [6,16,28,41,42] use conductive ink to enable paper-borne discrete buttons for a variety of productivity and entertainment uses. More complex circuits are also possible, such as *PrintSense’s* [20] capacitive matrix and *PaperID’s* [32] RF antennas. Finally, *PaperPulse* [48] and *PaperGenerators* [27] demonstrated the feasibility of embedding electronic components into paper circuits; *PrintScreen* [41] showed that basic visual output is even possible.

Although exact cost is not reported in any of the above references, we estimate that our approach is one or more orders of magnitude less expensive per sheet, embracing the fact that most paper is often used once, readily shared with no expectation of return, and ultimately discarded.

Technical Approach

Our sensing principle is based on electric field tomography (EFT), which is built upon electric field sensing (EFS). At a high level, this leverages the shunting effect, where a well-grounded object, such as a user’s finger, will draw a fraction of the current from the electric field to ground (see [47] for a more comprehensive explanation). Researchers have used EFS in many projects, including in-air finger tracking [19], touchscreen input [15,29], body motion tracking [11], and activity recognition [39]. EFT utilizes many EFS measurements to reconstruct a 2D or 3D estimation of the electric field through tomographic techniques (see e.g., [24] for more background). EFT has been used for e.g., in-air hand tracking [57,58] and hand gesture sensing [71,73].

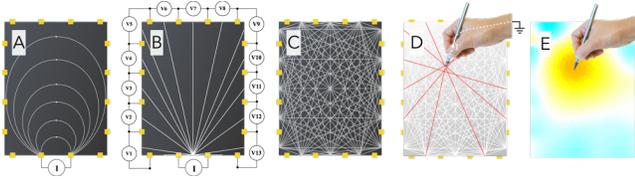


Figure 2. An overview of our sensing scheme.
See Sensing Approach section for details.

Our current work directly extends Electrick [72], which coated arbitrary objects with a conductive layer to enable EFT-driven ad hoc touch tracking. In this work, we adapted Electrick’s technical approach to a new domain, and in the process, considered fabrication methods and implications unique to paper, such as challenges arising from sheet thickness, sheet size, and support for writing implements and tokens. This focus also allowed us to achieve significantly better accuracies than reported in Electrick, which tested paper as one of its coating conditions, where it performed the worst (mean tracking error of 27 mm). Overall, the knowledge gained from our iterative prototyping, experimentation and user studies makes self-instrumented paper considerably more viable, and illuminates a new approach for researchers and practitioners exploring paper as a computational medium.

SENSING APPROACH

Figure 2 provides a simplified overview of our EFT sensing scheme. As we will discuss in the next section, our sheets of paper are augmented with a conductive backing and have traces running to 16 evenly-spaced points along the periphery of the interactive area. These traces run out to a common corner, to which our reusable sensor board connects.

One frame of data is captured as follows: Our sensor board generates a 200 kHz, 6 V_{pp} AC excitation signal using an AD5930. This signal is injected into our paper’s conductive backing using a pair of peripheral points (i.e., a *current-projecting pair*; Figure 2A), which are selected using two on-board multiplexers. The sensor board then measures the voltage at all other adjacent-point pairings (i.e., *voltage-measuring pair*), selected using a second set of multiplexers (Figure 2B). This signal is sampled by our board’s microcontroller (MK20DX256VLH7) ADCs at 4 MHz. Roughly ten periods of the excitation signal (200 samples) are collected for a root-mean-square (RMS) computation. To create a mesh of cross-sectional measurements, our sensor board rotates the current-projecting and voltage-measuring pairs until all combinations are measured (Figure 2C). With our 16 electrodes, this results in 208 RMS measurements, which are transmitted over USB at roughly 35 FPS.

When a finger (or conductive object in general) touches our paper’s surface, a small amount of current is shunted to ground due to capacitive coupling. This creates a localized voltage reduction, which manifests in the sensed mesh (Figure 2D). Using tomographic reconstruction, we can resolve touch locations (Figure 2E). More specifically, we created a finite element model (FEM) for each size of paper we ex-

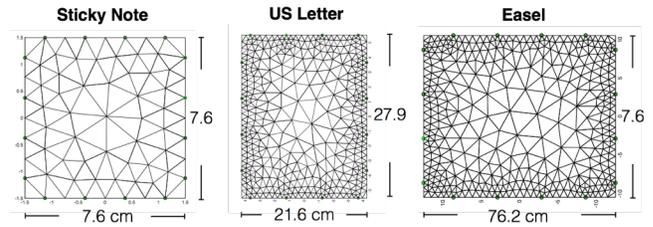


Figure 3. Finite Element Models for papers of different sizes.

plored using Netgen [54] (Figure 3). Our reconstruction solver is built on the Eidors’ [63] implementation of a modified Gauss-Newton solver [1]. This solver requires a one-time precomputation step to generate a reconstruction matrix, which takes about 2 seconds on a 2015 MacBook Pro (2.7 GHz Intel Core i5). After initialization, live image reconstruction requires a single matrix multiplication taking roughly 0.13 ms per frame.

Of note, capacitive sensing is inherently sensitive to grounding condition [47]. In our setup, both the sensor board and the user’s body capacitively couple to common ground (i.e., the Earth) to complete the circuit. Larger sensor ground planes offer stronger capacitive coupling, and thus result in a larger shunting current and superior SNR. For all of our explorations and studies, our sensor board was connected to a 15” Macbook Pro laptop over USB, which offers a fairly substantial ground plane. Future work remains to make our technique truly self-contained in a small, mobile package.

“PAPER PROTOTYPING”

Over the course of several months, we considered a wide range of candidate, conductive substrates. Most materials were eliminated from our list due to incompatibility with high-volume, low-cost production, such as materials with high cost (e.g., silver inks [13]) or unscalable fabrication processes (e.g., vapor deposition). We also dropped some materials for having poor interaction with paper (e.g., curling, bubbling). Other materials proved challenging to work with (e.g., achieving constant thickness of conductive silicone and conductive rubber). Lastly, many popular conductive films, such as ITO, PEDOT and carbon fiber, were often too conductive for our use (our identified ideal surface resistivity is 1 to 100 kΩ/sq).

Ultimately, we selected two materials that matched all of our criteria (which coincidentally happened to be the same as those identified in [72], which went through a similar selection process). The first is Velostat, a carbon-loaded plastic sheeting manufactured by SCS [12], which has a surface resistivity of ~ 70 kΩ/sq. We purchased a single .004”×54”×150’ roll for \$190 online [44] (28 cents per square foot). We adhere this backing to our paper with a 3M multipurpose spray adhesive. Our second substrate material is MG 838AR, a carbon-loaded paint manufactured by MG Chemicals, sold in one gallon cans online for \$295 [38]. A single coat can cover approximately 450 sq/ft (65 cents per square foot) and results a surface resistivity of roughly

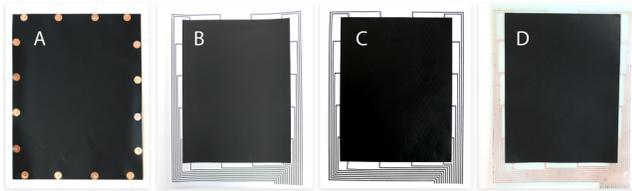


Figure 4. Fabrication methods we explored. A) Copper electrodes with hand-soldered wires, B) silkscreened pattern, C) cut-and-peeled conductive film, and D) conductive film with cut copper pattern.

1kΩ/sq. Without doubt, these costs could be dramatically reduced in mass production.

Our very earliest prototypes were handmade, using copper stickers adhered to the conductive backing with hand-soldered wires (Figure 4A). While this allowed us to validate our general approach, it was also untenable for mass production. We additionally found our EFT signal to be unstable, chiefly due to interactions between free-floating wires. Nonetheless, these early prototypes allowed us to quickly experiment with a range of design parameters. For example, we tested different numbers of electrodes, and found 16 to yield the best results (see also Discussion section). We also experimented with various application methods, especially for our conductive paint.

Iterating on our initial findings, we set out to create an *integrated* paper sheet design, containing both the conductive substrate and all necessary traces. For our paint substrate, we achieved the best results with silk-screening (Figure 4B), which suggests success with similar industrial-scale processes like offset printing. For our plastic sheet backing, we found subtractive methods to be the most effective. Specifically, we used a laser cutter to cut a trace pattern, which can be peeled from the paper (Figure 4C). We also experimented with cut copper film for the traces (Figure 4D). Either method could be achieved at scale with e.g., die cutting or stamping. In subsequent testing, we found our plastic-backed paper with copper traces provided the best SNR and stability, and this became our reference design for all subsequent evaluations.

PAPER SELECTION

Satisfied with the performance of our conductive layer, we turned our attention to optimizing the surface layer of paper. Although there are many different processes, surface treatments and pulp formulations used in the manufacture of paper, we found that thickness was the chief factor that correlated with performance (Figure 5, $R^2=0.96$). Our results suggest that the strength of capacitive coupling is linearly affected by the thickness of the dielectric paper layer. Figure 5 plots the results of our most insightful experiment, which measured shunting current through the finger for ten paper samples ranging in thickness from 0.03 mm (13.5 lbs) to 0.41 mm (129 lbs). Although thinner is better, there is a trade off in opacity if sheets are too thin (note that we did not even consider various super thin tracing or tissue

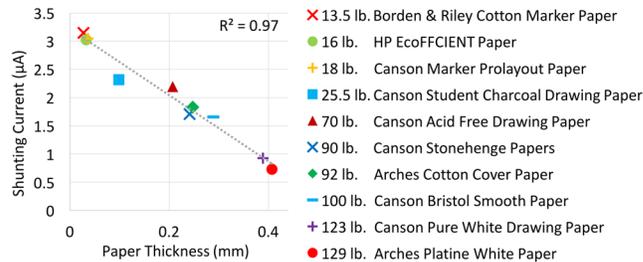


Figure 5. Shunting current across different paper thicknesses.

papers). Ultimately, we selected an HP EcoFFICIENT 16 lb. printer paper, which is bright white, offers excellent signal, and costs roughly 1 cent per sheet.

WRITING IMPLEMENTS

We also tested a series of writing implements to assess their feasibility. To enable shunting, the tip of an implement must be electrically connected to a substantial charge sink, such as a user. This is how passive styli made for capacitive touchscreens work, which also work with our technique. Conventional metal-body pens and metal-body brushes with a wet tip also work. Other implements generally need some modification.

We identified seven example implements of interest and measured their shunting current in the same manner as the study reported in Figure 5. Four of these implements required no modification (i.e., off-the-shelf): a metal fountain pen, metal ballpoint pen, touchscreen stylus, and metal brush (dipped in water). We lightly augmented the remaining three implements – a graphite pencil, a conductive marker and a calligraphy brush – with metal tape that connected to the graphite core, ink reserve, and brush tip respectively. Overall, there was not a large spread in shunting current across the tested implements (Figure 6), which ranged from 1.3 µA to 2.1 µA. This compares to 3.0 µA when a finger is touching the paper. As a representative writing implement, we selected the graphite pencil, which performed the worst in our test set, for our subsequent study.

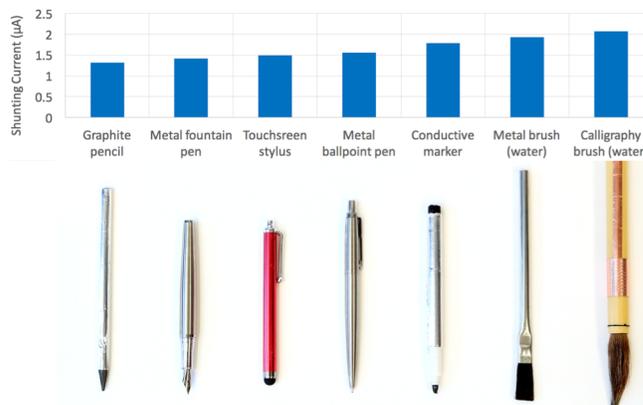


Figure 6: Shunting current of various writing implements, while gripped by a user, resting on our reference paper design.

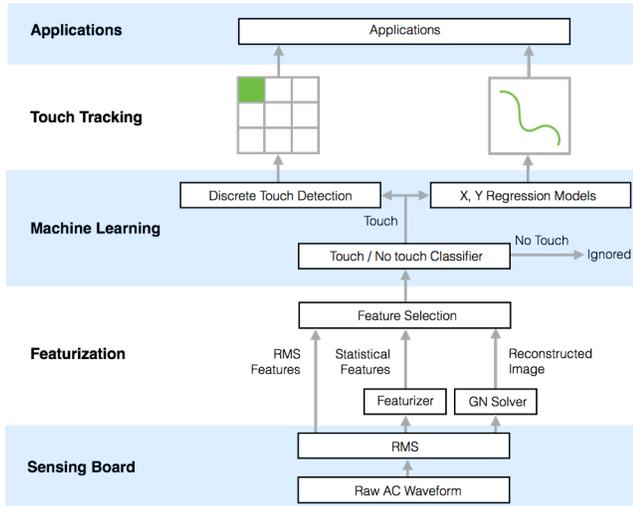


Figure 7. An overview of our touch tracking pipeline.

TOUCH TRACKING

To improve robustness against small variations in paper fabrication, as well as differences across users (e.g., finger contact area, grounding condition) and environments (e.g., ambient electromagnetic interference), we employ a machine learning approach for our touch tracking. This naturally identifies features that robustly characterize the signal across varying conditions, while ignoring noisy features.

We leverage two sets of features. First, we pass in the raw RMS values reported by our sensor board, as well as the mean, max, min, standard deviation, centroid and bin-wise subtractions. Second, we use the tomographically reconstructed values of the FEM, which varied by paper size (Figure 3 and Table 1). To prevent over-fitting, we train our classifiers on the most powerful 200 features selected by an information gain attribute evaluator with a Ranker search [22]. Note that this training must occur for each size of paper, but the resulting model is then portable across all sheets of the same size.

Our full pipeline is illustrated in Figure 7. Our first-level classifier is responsible for segmenting touch events: *touch* or *no touch* present (SMO, RBF kernel, $\gamma=0.07$). If a touch is present, the features are passed to two touch tracking classifiers that operate in parallel. The first is a discrete-touch classifier (SMO, RBF kernel, $\gamma=0.07$), trained on each crosshair location (as though it was a button). The second classifier is a pair of regression models (SMO, RBF kernel, $\gamma=0.01$) that produce a continuous X/Y touch position esti-

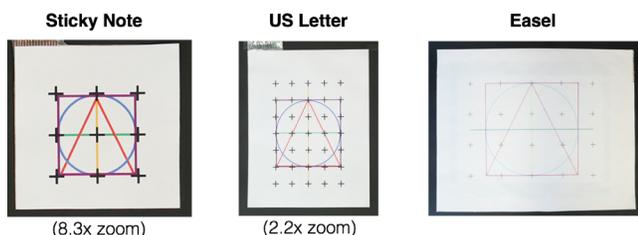


Figure 8. The three paper conditions used in the study.

mate. Output from these classifiers is used to power end user applications. Note that we did not implement palm rejection in our prototype, though it may be possible to distinguish between, e.g., a pen tip and a user’s palm based on the reconstructed image.

EVALUATION

To evaluate our approach, we conducted a user study with 11 participants (4 female, mean age 27). Importantly, interactive paper needs to work “out of the box”, without any user or world calibration. Therefore, we evaluated our system using a pre-trained model. Additionally, all participant input was computed and recorded live, purposely precluding any post-hoc “improvements” to the system or analysis.

Apparatus

We tested three different, yet common paper sizes (Figure 8). An obvious choice was US letter (roughly equivalent to A4), which is ubiquitous. We then selected paper examples an order magnitude smaller and larger: sticky notes and easel sheets (see Table 1 for dimensions). To standardize our paper thicknesses, we bought 16 lbs. US letter and easel paper; our sticky-note note condition was cut from this larger stock. On each paper size, we printed a grid of crosshairs and five shapes (horizontal line, vertical line, circle, triangle and square). The number of crosshairs and the interval between them varied by paper size (see Table 1). These three paper conditions are shown in Figure 8.

Paper Condition	Paper Dimensions	FEM Elements	Crosshair Configuration	Crosshair Spacing
Sticky Note	7.6 × 7.6 cm	110	3×3 (9 total)	15 mm
US Letter	21.6 × 27.9 cm	732	7×5 (35 total)	30 mm
Easel	76.2 × 63.5 cm	714	4×5 (20 total)	120 mm

Table 1. Specifications of our paper conditions.

In addition to our three paper sizes, we also evaluated two input modes: finger and graphite pencil (Figure 6). Due to the reduced shutting current when using the pencil, we plugged our laptop into wall power, which provided an improved ground for this condition only. This made our study a 3×2 design resulting in six test conditions, specifically *Sticky Note Finger*, *Sticky Note Pencil*, *US Letter Finger*, *US Letter Pencil*, *Easel Finger* and *Easel Pencil*.

Procedure

We employed the same procedure for all six of our test conditions, the order of which was randomized. In each, participants clicked every crosshair, as instructed by a simple visualization running on a laptop. One round consisted of 30 trials of a participant keeping their hands away from the paper (i.e., no touch), and one trial of touching each crosshair (the number of which varied by paper size; see Table 1). Four rounds of this procedure were completed. The live output of our discrete classifiers and continuous touch tracking models was recorded. To specifically test continuous touch tracking, we included an additional experimental task in which participants traced shapes printed on our paper conditions (Figure 8). Each shape was traced

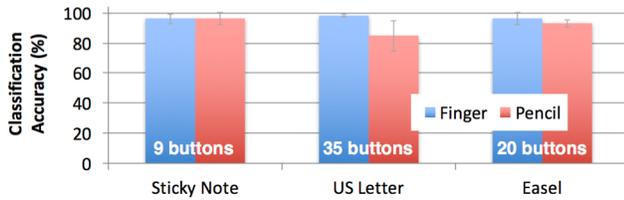


Figure 9. Discrete touch location classification accuracies.

three times. In total, this procedure yielded 7920 *no touch* trials, 5632 *crosshair click* trials and 990 *traced shape* trials. The study took roughly 60 minutes and paid \$10.

RESULTS

All reported statistics are based on the live performance of our system with no per-user calibration or correction. All figures use standard deviation for their error bars.

User and Environmental Effects

A central motivation for running a user study – as opposed to a more straightforward technical evaluation – was to see if there were any per-user effects, stemming from variations in e.g., footwear, skin condition and hydration. These factors can affect capacitive coupling and grounding condition. However, these small user variances had no discernable effect on our system’s performance. Similarly, we ran our study across several days, with e.g., varying humidity and ambient temperature. Although obviously not exhaustive, we did not see any change in accuracy.

Touch Detection Accuracy

Our first-level, touch/no-touch classifier achieved a mean accuracy of 97.2% across participants (SD=1.8). Of these errors, 2.5% of trials were classified as touches when no finger or pencil was touching the paper, and 0.2% actual touches were missed. There was no significant difference between conditions.

Discrete Touch Location Classification

When using a finger for input, our discrete touch location classifier achieved an average accuracy of 96.8% (SD=2.8). This accuracy drops to 91.4% (SD=5.6) when using the pencil for input. A paired t-test shows this difference is only significant in the US Letter condition ($p < .05$), which also had the highest number of discrete touch locations (35 classes). Figure 9 illustrates these results.

Continuous Touch Tracking Accuracy

Strokes captured from all participants are overlaid, without correction, in Figure 10. Overall, our approach achieves a mean distance error of 14.3 mm (SD=3.5) when fingers are

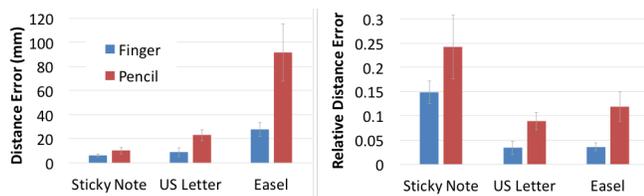


Figure 11. Continuous tracking error across conditions. Left: Absolute distance error. Right: Error relative to paper size.

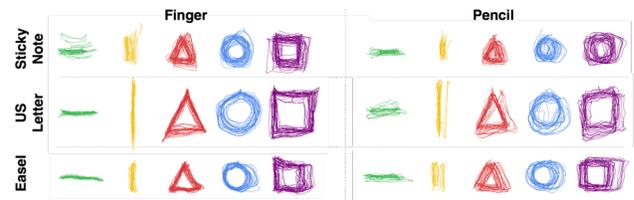


Figure 10. All participant strokes overlaid.

used. Pencil input is significantly worse (paired t-test, $p < .05$), with a 41.6 mm mean distance error (SD=10.3). Looking at Figure 11 (left), it is apparent that error increases as paper size increases. Of course, different sizes of paper are used for different tasks; for example, precision tends to be greater on sticky notes than paper easels. Thus, we also plot these results relative to paper size in Figure 11, right, which largely negates this trend.

TWO-POINT TOUCH TRACKING

Using the same participants, we conducted a supplemental study to investigate the feasibility of basic multitouch sensing, specifically two-point sensing (most common after single finger inputs). For this, we used our US Letter paper condition and a simple visualization running on a laptop that highlighted two crosshairs at random (i.e., a random separation distance) for the user to touch simultaneously in a bi-manual fashion. In total, 25 crosshair pairs were requested. Our machine learning pipeline was not designed for multiple touch points, so we used our tomographic reconstruction in concert with standard blob tracking [37].

Accuracy results are shown in Figure 12. In general, touch points separated by at least 17 cm achieved segmentation accuracies exceeding 80%. In trials in which two fingers were correctly detected, results show a mean distance touch tracking error of 23.9 mm (SD=4.3). While far from immediate feasibility, we believe this result suggests that signal is present and that coarse multi-touch may be possible in future work.

DISCUSSION & LIMITATIONS

Resolution vs. Electrode Count

In general, more electrodes result in a denser mesh of cross-sectional measurements, yielding higher tracking resolution. However, this only works up to a point, as electric field tomography suffers from the “soft field problem” [24] caused by non-linear electrical paths with incomplete occlusion (unlike e.g., optical sensing). This causes any shutting point to affect measurements at all electrodes, which undermines the benefit of higher electrode count. Additional-

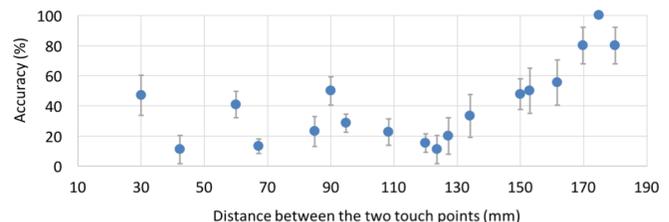


Figure 12. Detection accuracy for two-point multitouch inputs.

ly, more electrodes increase the number of measurements needed per frame, reducing frame rate. For our current hardware, we found 16 electrodes to be a sweet spot in accuracy and framerate. However, future systems with improved sampling rate and sensitivity might benefit from higher electrode counts.

Sensing Electronics

To keep cost low, we separated the (expensive, reusable) electronics from the (inexpensive, disposable) interactive medium. This approach requires a quick and easy way to connect paper to the sensing board, for example a clip (Figure 1) or other connector. That said, one day, it should be possible to include the electronics directly in the paper itself. This has already been demonstrated with eInk displays for magazine covers, singing birthday cards, and RFID tags, all of which contain simple microprocessors so inexpensive they can be discarded.

Double-Sided Paper

All of our prototype sheets were single sided – paper on one side, conductive layer on the other – reducing space for content. This could be partially remedied by simply sandwiching the conductive layer between two sheets of paper. However, our technique currently cannot disambiguate which side is being touched, so printed content would have to be designed so as to avoid mirrored ambiguities (e.g., multiple choice boxes that do not overlap front-to-back).

Bending, Folding and Other Physical Manipulations

We did not set out to create a flexible touch sensing technology, though our technique can act as one. Although paper has rich (and well-studied [17,18,23,25,31,59]) physical affordances, we choose to focus on common table-based interactions, chiefly writing and drawing. A proper exploration of dynamic and gestural physical manipulations was beyond the scope of our technically-oriented investigation.

Cost at Scale

As mentioned earlier, the material cost of our plastic-backed paper design was around \$0.30 per sheet at retail prices. While cheap for a touch panel, it is still expensive for a sheet of paper. Cost would have to be reduced by another order of magnitude in order to be commercially feasible. Fortunately, mass production can offer such dramatic reductions. As one point of comparison, we can look to commonplace consumer products that have similar material properties to our approach. For example, many paper products today are sold with plastic or painted coatings, such as milk cartons, disposable paper cups and tear-resistant envelopes. The existence of these single use items, costing mere cents, suggests manufacturing feasibility.

Recyclability

Another great benefit of paper is its recyclability. In developed countries, a majority of paper is now recycled and reused [62]. Although a full discussion is beyond the scope of this paper, we did investigate the feasibility of recycling our proof-of-concept paper. We found that our paint-coated sheets are likely recyclable through conventional solvent-

based methods used to wash ink from recycled pulp. Our plastic-backed sheets would likely go through similar separation processes as other plastic laminated paper products, such as juice cartons and disposable serving containers [9]. The latter process could be facilitated by using a dissolvable adhesive between conductive and paper layers.

Environmental Noise

Electromagnetic noise emitted by power lines, fluorescent lights, and electronic appliances can affect the tracking accuracy of our system. To mitigate this interference, our sensor board includes a high pass filter before the ADC pre-amp. Superior analog filters, signal processing, paper construction and trace material could no doubt reduce this further, but we leave this optimization to future work.

Grounding Condition

The biggest obstacle we encountered is limited shunting current due to poor grounding, which makes touches challenging to localize. This is a universal issue for electric field sensing systems [47], and researchers have proposed several ways to provide superior ground planes [7]. An ADC pre-amp with larger input impedance may also help combat this issue and improve SNR. Fortunately, we found finger input to be reliable irrespective of grounding condition. However, the added impedance when using a writing implement forced us to ground our laptop to wall power in the user study (pencil condition). This, however, is not a hard requirement; e.g., you can see ungrounded pencil input throughout our Video Figure. In short, this is an unsolved problem for both our system and many others, and future work is needed. Fortunately, as evidenced by the capacitive screens in our smartphones, it is likely that with sufficient engineering, this problem can be overcome.

EXAMPLE USES

We created a series of simple, but functional example applications to illustrate the feasibility and potential utility of our technique. These applications were selected to demonstrate inputs from both fingers and implements, across a range of paper sizes and use domains. Please also see Video Figure.

Print Media

Although being supplanted by online media, newspapers, magazines and other printed material are still read by millions today. With paper being static, there is no easy way for readers to more deeply engage with printed media. One possibility is to have integrated printed “buttons” (Figure 13A), which could allow for readers to e.g., rate articles, share stories on social media, add items to a digital reading list, and launch content on accessory devices.

Education

Textbooks, handouts and paper exams continue to be commonplace in education settings. As one example in this domain, we created an interactive math exercise containing both multiple choice and fill-in-the-blank written answers, which is graded in real-time and could offer live instructional feedback (Figure 13B).



Figure 13. We created several illustrative applications.

Digital Notes

Compared to most digital systems, paper still provides a more flexible and rapid means to draw and write. For this reason, notepads, easels, post-it notes and similar are still popular today. We want to retain this key benefit, but it would also be nice if notes on these surfaces were automatically digitized (Figure 13C) for e.g., transmission to others.

Board Games

As a mass consumer item, many games are made from paper, whether it be a book of Sudoku puzzles or a board game. As one example, we created an augmented version of Snakes and Ladders, which can track the state of the game, enforce rules, and play sound effects (Figure 13D).

CONCLUSION

We have described a new approach for creating touch-sensing paper. We reported the outcomes of our search for compatible fabrication methods and materials, and discussed how we can support tracking of both fingers and implements. We quantified the performance of our touch tracking through a user study, which suggests the overall approach has merit. Although much future work remains, we believe this illuminates one possible approach for achieving low-cost, interactive, paper-based experiences in the future.

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