ABSTRACT

This pictorial presents a design investigation at the intersection of paper and computer vision for tangible interfaces. Through this exploration, we uncovered various characteristics of paper that connect tangible interactions with concealing and revealing printed fiducial markers for detection—particularly through the affordances of paper craft and fiber. We illustrate a variety of paper structures that construct and deconstruct fiducial markers. We also demonstrate how these structures enable untethered functional physical inputs, such as push buttons and sliders. We showcase four proposals that extend these material insights into tangible interface applications, including interactive data physicalizations and functional paper prototypes. Furthermore, we continue the legacy of pictorials by exposing fabrication drawings for others to engage with this work at a more practical level.
INTRODUCTION

There is a spotlight on materials within the HCI research community [43–45]. Researchers have engaged with different agendas while examining the materiality of computational systems—from frameworks that describe the structure of computational composites [38,45], to methods for engaging with materials [12,17,27,42]. In addition, there is a burgeoning body of work that investigates specific physical materials and their applications for interaction design (such as textiles [3,7,28] and paper [24,25,39]).

This pictorial presents a design-driven inquiry into paper as a material for computational composites. Paper is familiar, accessible, and can be easily shaped into a variety of three-dimensional forms [21]. Within HCI, researchers have explored paper as a medium for computational construction kits [4,10,23,32], as well as an alternative form of electronics for sensing [13,37,46] and actuating [31,39].

In this work, we explore in tandem two seemingly disparate affordances that paper offers for tangible interactions—paper as a printing medium for fiducial markers; and paper as a medium for creating pliable 3D objects. From this investigation, we uncovered a variety of tangible interactions that can be detected through different paper structures that construct and deconstruct fiducial markers. These paper structures are easy and economical to fabricate. Furthermore, many interactions can be sensed via a single camera.

This pictorial details the paper structures explored and the tangible interactions they afford. We also demonstrate four potential applications with the insights we uncovered.

RELATED WORK

Paper for tangible interfaces

Paper is an accessible medium for tangible interfaces. For example, researchers have explored the craft affordances of paper with DIY electronics to create interactive books [30,32]. Paper-based composites have also been explored for functional sensing, such as carbon-coated paper or paper with inkjet printed circuits for sensing deformations in paper structures [5,13,14,37,46]. Furthermore, through this method of selectively depositing materials on paper, researchers have combined both touch sensing and physical actuation into paper structures [26,39]. In this work, we explore computer vision and deconstructed fiducial markers as a material parallel to electronics for functional tangible paper interfaces.

Computer vision for tangible interfaces

We are drawn towards computer vision as an alternative to built-in electronics for sensing inputs in a tangible interface. Such an approach affords untethered and thus free moving inputs. Researchers have proposed tabletop vision-based interfaces, notably reacTable [16] for music synthesis and the accompanying reacTIVision platform [33], Madgets for sensing and actuating input widgets [40], SLAP widgets for physical inputs with dynamic displays [41], as well as Arcadia for rapidly prototyping interface layouts [20]. Other researchers demonstrate embedding the camera in the interior of a tangible interface to sense inputs on a 3D object. Sauron [34] offers a toolkit of customizable inputs fabricated via 3D printing and recognized with a proprietary detection software. Similarly, [8] describes a “vision core-interface shell” strategy for implementing vision-based 3D interfaces.

Designable fiducial markers

Typical fiducial markers such as barcodes or QR codes stand out from their surroundings as they are highly structured and recognizable objects. In contrast to these marker dictionaries, researchers have developed a designable visual marker protocol, d-touch [6]. Researchers have extended this protocol to embed digital information into interactive decorations, and applied it to wallpaper, ceramics, and musical instruments [1,29]. We are inspired by this unexpected intersection of graphics for both computer vision and aesthetics—and in this work, we explore “misusing” printed fiducial markers through the materiality of paper to support tangible interactions.
THE AFFORDANCES OF ARUCO MARKERS

In this exploration, we used the 4×4 ArUco marker dictionary [11] for fiducial markers. Each marker provides information on its position, orientation, and identity (in the form of an integer). ArUco marker detection is packaged within OpenCV [47], and we developed a Python script which enables us to modify its CV (computer vision) detection parameters. This script also broadcasts marker data through a WebSockets server, which we used for developing the applications presented later in this pictorial. We constrained ourselves to grayscale markers in our exploration and noticed that detection is most effective when the dark border is continuous. Furthermore, a marker is more effectively detected when placed within a lighter region. These detection affordances informed how we approached exploring tangible interactions with paper and printed markers.

For each prototype, we used an adjustable stage to facilitate ArUco marker detection. This stage employs a set of magic arms to hold an acrylic plate relative to a camera.

EMBEDDING PRACTICAL DESIGN FILES

Communicating research at the intersection of materials, design, and interaction often takes on a more visual nature. DIS pictorials have been an ideal platform to communicate such work—from visually highlighting details [2,22], documenting process [18], to providing making templates [46]. This pictorial extends the platform by embedding fabrication files as vector thumbnails; reducing the page real estate of peripheral information, while preserving the role of this pictorial as a workbook for others to take up their own explorations. We illustrate shrinking a fabrication file into a small frame below. These frames are distributed throughout the pictorial alongside their corresponding examples.

To use these fabrication files, open the PDF page with a vector editing tool (such as Adobe Illustrator) and scale them up accordingly. Print, cut, fold, and glue these patterns according to the schematic annotated below.

For each prototype, we used an adjustable stage to facilitate ArUco marker detection. This stage employs a set of magic arms to hold an acrylic plate relative to a camera.
EXPLORING PRINTED PAPER MARKERS FOR TANGIBLE INTERACTION

Fiducial markers support tangible interactions through free-moving tokens that report their position, orientation, and presence [16,41]. For our exploration, we focused on investigating tangible interactions which employ the material characteristics of paper to conceal and reveal printed fiducial markers. In this section, we showcase examples that were reliably detected with computer vision, while making use of paper’s physical affordances. We organize our exploration into two broad categories: First, paper craft manipulations that rely on paper’s affordance for cutting, folding, bending, and gluing. Second, paper fiber manipulations that leverage paper’s material composition.

All experiments were conducted with 80gsm letter-sized printing paper. We employed manual tools to work with paper during our exploration, including paper knives, scissors, scoring pens, and glue. For higher presentation quality, we used a laser cutter to fabricate examples in this pictorial.

Papercraft

Constructing markers with paper edges

Markers can be printed (or drawn) on the edges of a stack of paper. Such markers are only revealed when the paper stack is sufficiently compressed. We demonstrate this with a paper spring made from interweaving two strips of paper. This spring has a series of printed patterns on its folds, which reveals a marker when the spring is fully compressed.

Papercraft

Marker completion through collapsing paper folds

A strip of paper is symmetrically scored into multiple segments. When the ends of this strip are pushed together, the inner folds collapse and another pair of segments meets in the middle. With this in mind, we divided markers into left/right halves, and arranged these halves as shown in the schematic. A different marker is therefore completed and detected when the strip collapses to a new segment.
Papercraft

Push buttons through marker completion

Folded sheet material structures can translate movements from one axis to another and have been applied to mechanisms such as lifting [19]. Through our exploration, we designed two types of simple button mechanisms that translate a push, to movements that complete a printed marker for detection. We showcase two variations for each type of button—a simple variation, and another with more folds. These additional folds stiffen the paper’s structure and increase the force feedback (“springiness”) when pushing the button.

Symmetrical Button

In its simplest form, the symmetrical button comprises a “Z” fold on each side. Pushing this paper button brings both halves of the marker together.

Asymmetrical Button

In its simplest form, the asymmetrical button comprises a flap held up with a series of pleated folds. Pushing this paper button lowers the flap and completes the marker. As a heuristic, this button is detected more reliably when compared to the symmetrical button as it uses only one moving flap for marker completion.

To minimize false positives for each button version (detecting a complete marker when the button is not pressed), we recommend positioning the camera to maximize its view of the gap between the marker halves.
**Papercraft**

**Marker deconstruction with stretchable paper structures**

Stretching structures can be introduced into sheet materials through a series of alternating dashed cuts, and HCI researchers have explored embedding circuits in these structures to sense deformation [14,46]. We extend this line of investigation and approach sensing such structures through printed markers and computer vision.

We printed a marker over the stretching structure—this marker is detected at rest. When stretched, widening gaps break up the marker border and detection is lost. Furthermore, we observed that the paper structure stretches more in the middle than at the ends; markers thus lose detection at different degrees of stretching based on where they are placed. In the example here, the middle marker loses detection at 10% stretch, while the end markers lose detection at 23% stretch.

**Paper fiber**

**Tearing printed paper markers**

Paper easily affords tearing—an experience that arguably fills us with both satisfaction and dread. We are drawn to the emotive qualities of this interaction, and also the notion of irreversible actions in a tangible interface. Paper can be directed to tear along a line through an initial cut or perforation. In this example, we guide a tear through a column of different markers. Torn markers lose detection, which we use to determine the length of the tear.
**Paper fiber**

**Wetting printed paper markers**

Cellulose-based paper turns translucent when its fibers soak up water. We leverage this phenomenon to conceal markers when wet and reveal them when dry. To achieve this, we placed the printed paper marker over a black background. We adjusted the print contrast such that it is just above detection threshold when dry. When wet, the paper becomes translucent which reveals the darker print below. This decreases the marker's contrast with its surroundings and detection is lost.

**Lighting printed paper markers**

Paper is commonly used in lamp shades and screen dividers to diffuse light. Like wetting, we explored paper's translucency with light to reveal and conceal markers. In this example, we placed a blank sheet of paper directly on top of a printed paper marker. This hidden marker is revealed and easily detected when illuminated from behind.

**APPLICATION PROPOSALS**

The material exploration uncovered different techniques for tangible interactions with printed paper markers. We extend these techniques and applied them to four different proposals for tangible interfaces.

Applications include DIY interactive data physicalization, embodied storytelling through an interactive pop-up book, functional paper prototyping for physical interfaces, as well as a delicate—and disposable—game controller.
Interactive Bar Chart

We used the symmetrical button type to indicate data points on a bar chart. The longer bars have a series of duplicate markers along their length—this ensures that a press is detected at any point along the bar.

Interactive Line Chart

We used the asymmetrical button type to indicate data points on a line chart. In this example, the button was designed to complete a subregion within a larger marker. This enabled us to keep the button/data point small to minimize clutter on the data physicalization, while ensuring effective detection with a big marker.

Application Proposal

Interactive Data Physicalization

Physicalizing data presents many benefits, including making abstract information more accessible by leveraging our perceptual-motor skills of interacting with the physical world [15]; and paper offers an economical approach for DIY data physicalizations. We applied ideas from investigating paper push buttons to this context to make an interactive bar and line chart. Each data point is indicated by a push button. These raised buttons are shaped to represent data points on the bar and line chart through shape and position respectively. We connected these interfaces to a web page with text-to-speech capability. The web page reads out information about the data point when it is pressed, as well as comparative information when multiple data points are pressed.
Application Proposal

Embodied Storytelling through Interactive Pop-up Books

Pop-up books employ pliable paper structures to physically enact different narratives for storytelling. We see an opportunity to connect such interactive books with other content forms by incorporating printed paper markers. With this in mind, we connected two different paper structures to concepts within plate tectonics: convergent and divergent plate boundaries. Each page is paired with a Processing sketch that provides animated content triggered by interacting with the pop-up structures.

Divergent plate boundaries

We adapted the stretchable paper structure to embody divergent plate boundaries. The page was organized such that stretching this structure reveals a red background; embodying the concept that molten rock fills the gap when plates separate to create new land. Printed markers at the end of this stretchable structure lose detection when stretched. This triggers an animation of how new land is formed with this plate boundary.

Convergent plate boundaries

We employed the collapsing paper structure to embody convergent plate boundaries. Pushing this structure together extends a red ribbon into the pop-up flap; embodying the concept that plates sink and form molten rock when plates collide. A different marker is completed for each collapsed segment, which is used as keyframes to display different annotated diagrams about this plate boundary.
Application Proposal

Physical Paper Prototyping

We explored printed paper markers for rapidly prototyping functional physical interfaces. Extending the techniques explored and the affordances of ArUco markers, we developed three input components—push buttons (using the symmetrical button), sliders, and knobs. These components were used to prototype a MIDI controller that comprises 14 buttons to play notes, 2 sliders to modify the sound envelope, and a knob to affect volume. These components are detected through a single camera and sent to Processing sketch to generate sounds. Furthermore, paper enabled us to easily explore the visual aspects of this controller through printed graphics—such as color, material, and surface finishing. We elaborate on the design of the slider and knob.

Slider

The slider is constructed by physically connecting a series of symmetrical buttons with unique markers. Pressing on this slider completes the marker(s) directly below the point of contact; we can then use the identity of detected markers to approximate where the slider is pressed.

Knob

The ArUco library provides the coordinates of detected marker corners. We use these coordinates to calculate the knob’s rotation.
Application Proposal

Delicate Game Controller

The delicate nature of paper affords tangible interfaces that have irreversible interactions. With this in mind, we developed a novel game experience dubbed “Paper Paddles”. In this game, two players race their boats down a river. Each player has a paper controller consisting of two stretchable tabs that they pull and release to paddle left or right. Each tab is attached to a flap with a printed marker designed such that pulling hard on the tabs will tear through this marker. The game encourages players to row fast enough to stay ahead—but not so vigorously that they tear their controller. Furthermore, the delicate nature of paper makes it easy for players reach over and sabotage their opponent’s controller. Tearing a tab disables the paddle in the game, and players have to swap their damaged paper controller for a new one.

Paper Paddles offers a contrasting (and lighthearted) take on game controllers. While conventional game controllers are designed to be robust devices that deliver “ready-at-hand” experiences [9], the delicate nature of this paper controller integrates breakdown into the gameplay itself—encouraging players to pay more attention to the interface in their hand.

Pulling and releasing the paper paddles.
DISCUSSION

We started this work motivated to explore a form of computational composites enabled by paper and computer vision. Printing enmeshes new visuals and materials into the substance of paper—this inspired us to connect the affordances of printed fiducial markers with the legacy of paper as a material for making. With this motivation, we investigated various ways of manipulating paper for tangible interactions; through paper craft techniques or affecting its fibers. We also extended the ideas from our exploration and proposed four applications for the design of physical interfaces.

As designers, we were more familiar with computational composites that incorporate electronics into material assemblies (e.g. embedding electronics into textiles [3], concrete [38], and even ice [45]). Creating such composites requires designers to consider both physical materials and electronic circuits. Printed paper markers challenged this approach towards computational composites. Rather than microcontrollers and circuits, our investigation required us to attend to “immaterial” concerns [36] such as lighting and contrast, camera angle and resolution, as well as ArUco detection parameters. This introduced a different set of tensions. For instance, printing and folding inconsistencies which our eyes intuitively correct are instead amplified by the camera. The detection script we developed therefore became an invaluable debugging tool to assess the integrity of each printed marker. Analogous to a soldering iron for repairing electronic circuits, we used a simple black pen to “fix” printing and folding errors by drawing over them.

The ideas and techniques we present in this pictorial are not without their limitations. As mentioned earlier, one drawback is the contextual sensitivity of our detection set-up. As lighting and contrast play a huge role in detection performance, we had to tweak detection parameters when the system moved between locations. Another drawback is the visual presence of the ArUco markers—tangible interfaces made with this technique might be limited in terms of graphical flexibility. Just like placing barcodes on products, fiducial markers take up space and can disrupt the visual quality of an interface (e.g. the pop-up book example). Having said that, printed paper markers served as an open-ended canvas for experimenting with different pliable structures for tangible interaction. Through paper, we were able to combine complementary affordances, such as 3D shapes for data physicalization that also functioned as interactive buttons, or collapsible structures for a pop-up book that also enacted its narrative. Furthermore, with Paper Paddles we had the opportunity to combine contradictory affordances to probe a new interactive experience for game controllers.

We are inspired to extend our investigations into computer vision and computational composites. We plan to develop a mobile version of the detection script as a more portable means of working with printed paper markers. During our exploration, we also experimented with using an IR (infrared) camera to detect fiducial markers, following the set-up described in [35]. Through our initial experiments (shown in the right panel), we observed that some inks which are clearly visible to the naked eye are invisible to the IR camera. Different inks could therefore be applied on a paper interface to create layered graphics for information as well as detection. Finally, we want to explore more open-ended marker generation techniques that offer designers more flexibility in terms of layout and visuals, such as d-touch [6], or employing complex images as markers.

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