

# PaperWindows: Interaction Techniques for Digital Paper

David Holman, Roel Vertegaal, Mark Altosaar  
 Human Media Lab  
 Queen's University  
 Kingston, ON, Canada K7L 3N6  
 {holman,roel,altosaar}@cs.queensu.ca

Nikolaus Troje and Derek Johns  
 Department of Psychology  
 Queen's University  
 Kingston, ON, Canada K7L 3N6

## ABSTRACT

In this paper, we present PaperWindows, a prototype windowing environment that simulates the use of digital paper displays. By projecting windows on physical paper, PaperWindows allows the capturing of physical affordances of paper in a digital world. The system uses paper as an input device by tracking its motion and shape with a Vicon Motion Capturing System. We discuss the design of a number of interaction techniques for manipulating information on paper displays.

## ACM Classification Keywords

H.5.2 [Information interfaces and presentation]: User Interfaces.

## Keywords

Digital Paper Interfaces, Flexible Displays, Ubiquitous Computing.

## INTRODUCTION

In recent years, considerable progress has been made towards the development of thin and flexible displays. A range of flexible electronic devices, including full color, high-resolution flexible OLED displays with a thickness of .2 mm have recently been introduced to the market [13]. The goal of such efforts is to develop displays that resemble the superior handling, contrast and flexibility of real paper. Bendable interfaces such as ShapeTape [1] and Gummi [17] already demonstrate the value of incorporating the physical shape of objects as computer input. Although wireless full color paper displays are not yet available, prototype paper displays exist that demonstrate their future potential. In this paper, we present PaperWindows, a prototype windowing environment and set of interaction techniques that allows us to examine how we might bridge the divide between the digital and physical world of computing via paper interfaces.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

CHI 2005, April 2-7, 2005, Portland, Oregon, USA.

Copyright 2005 ACM 1-58113-998-5/05/0004...\$5.00.

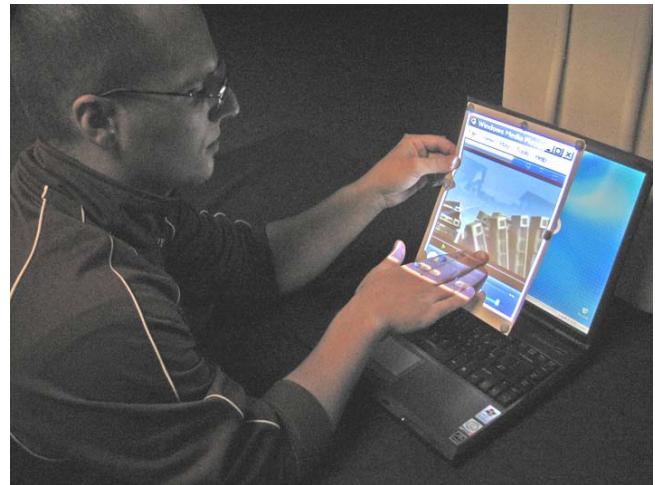


Figure 1. A rubbing gesture transfers a window to augmented paper.

The advantages of paper over the windowed display units used in standard desktop computing are manifold [18]. For example, documents presented on paper can be moved in and out of work contexts with much greater ease than with current displays. Unlike GUI windows, paper can be folded, rotated and stacked along many degrees of freedom [6]. It can be annotated, navigated and shared using extremely simple gestural interaction techniques. In this way, paper allows for greater flexibility in the way information is represented and stored, with a richer set of input techniques than currently possible with desktop displays. By contrast, digital systems support properties unavailable in physical paper, such as easy distribution, archiving, querying and updating of documents. By merging the digital world of computing with the physical world of paper displays we hope to improve the richness and value of both technologies.

PaperWindows is an environment that allows us to simulate the use of digital paper. By projecting windows on physical paper, PaperWindows allows us to digitally utilize the physical shape of paper. By sensing the user's interactions with real paper using computer vision, PaperWindows allows the use of paper as an input device. In

PaperWindows, users can place a window on a piece of paper with a simple rubbing gesture (Figure 1). Once transferred, paper windows can be held, laid out, or arranged freely to suit the task. Users can interact with the paper document using their hands, fingers, pen, or a set of gestures, within the context of the three dimensional motion and shape of the physical paper artifact.

To allow unrestricted movement of paper in the physical space, with as many degrees of freedom as possible, our system tracks the movement of paper windows using a Vicon Motion Capturing System [20]. This allows us not only to track the shape of a piece of paper, but also the movement of pens, fingers, hands and other objects in relation to the paper document. We will discuss how we designed a number of novel interaction techniques for manipulating information with paper windows. To copy a page to another piece of paper, users can use rubbing or stenciling gestures. To navigate pages, a flipping gesture is used. To provide overviews of larger documents, users can view multiple pages side by side, or transfer contents to a larger page. As such, the physical affordances of paper underlie a rich set of gestural interaction styles.

## RELATED WORK

### Ubiquitous Computing

PaperWindows was inspired by prior research on systems that aimed to merge the digital with the physical world. It is firmly based on the vision of Ubiquitous Computing as defined by Weiser [21]. PaperWindows is modeled as an interface that “takes into account the natural human environment and allows the [computer] to vanish in the background.” Like PARC tabs [21], PaperWindows provide an extension to computer-based displays: people may arrange tabs around their physical space in ways that are similar to paper-based projects. To move a project to another room, tabs can be picked up and carried – this behavior is copied in our system. Like PARC pads [21], paper windows are analogous to scrap paper that is “grabbed and used anywhere.”

PaperWindows also relates to more recent work in ubiquitous computing. SmartSkin [15] is an interactive surface that is sensitive to human finger gestures. With SmartSkin, the user can manipulate the contents of a digital table using fingertips, hands, or even their whole arms. Similarly, Rekimoto’s Pick and Drop [14] is a system that lets users drag and drop digital data among different computers as if it were a physical object. Each of these interfaces merges interactions in the physical world with interactions with one or more digital devices. In PaperWindows, we drew on this design concept, further blurring the boundary between physical paper and the digital information. In Ishii’s Tangible User Interfaces (TUIs) [4], interaction with digital information is provided through physical manipulation of real-world objects. PaperWindows adapts this concept to the use of paper as a display object.

### Flexible Displays

PaperWindows utilizes technology similar to Gummi [17]; it is a design concept that examines embodied interaction techniques through the use of a thin, bendable display. With Gummi, Schwesig et al. proposed a credit card sized computer that uses physical deformation of the device for browsing of visual information. Even though flexible displays are still in development, there will be an increased need for interaction paradigms that support the properties of this new medium. Although we were inspired by Gummi’s paradigm, we diverge from its focus as a mobile handheld device. Instead, PaperWindows studies the use of flexible displays in a more traditional workplace environment.

### Paper Based Design Principles

In the *myth of the paperless office* [18] Sellen analyzes the use of physical paper in two different environments: Xerox PARC research center and the International Monetary Fund in Washington, D.C. Based on her findings, she proposed the following set of design principles for incorporating affordances of paper documents in the design of digital devices:

1. *Support for Flexible Navigation.* Desktop computers impose three constraints that make spatial navigation in a document difficult: input is indirect, mainly one handed, and heavily dependent on visual cues. To reduce interference with reading and writing, navigational techniques should be employed that reduce the demand on the visual system. This is accomplished by providing a richer set of non-visual cues, more direct forms of input, and by supporting two-handed interactions.
2. *Support for Cross Document Use.* Paper supports the use of multiple documents. A single desktop display can make it very difficult to lay out multiple documents in parallel. At least two documents should be able to be viewed at once on the device. In the desktop setting, multiple displays and large screen sizes can make cross document use more practical. Even so, people often prefer the flexible and configurable nature of physical paper [12].
3. *Support for Annotation While Reading.* Paper supports easy annotation while reading. Annotation with desktop computers is still cumbersome and heavily dependent on keyboard and mouse. Although many applications support a revision feature (e.g. ‘Track Changes’ in Microsoft Word), it can be difficult to highlight parts of a text without altering its format.
4. *Support for Interweaving Reading and Writing.* With paper it is easier to mix reading and writing activities. However, most desktop computers do not support such parallel activities. Tasks such as reading, navigating, or typing are typically performed sequentially.

## Paper Interfaces

A number of prototypes have been developed over the years that aim to simulate certain aspects of the use of paper in a digital environment.

### Augmented Paper Interfaces

In *DigitalDesk* [22], a physical desk is augmented with electronic input and display. A computer controlled camera and projector are positioned above the desk. Image processing is used to determine which page a user is pointing at. Object character recognition transfers content between real paper and electronic documents projected on the desk. Wellner demonstrates the use of his system with a calculator that blurs the boundaries between the digital and physical world by taking a printed number and transferring it into an electronic calculator.

*Interactive Paper* [10] provides a framework for three prototypes. *Ariel* [10] merges the use of engineering drawings with electronic information by projecting digital drawings on real paper laid out on a planar surface. In *Video Mosaic* [10], a paper storyboard is used to edit video segments. Users annotate and organize video clips by spreading augmented paper over a large tabletop. *Caméléon* [10] simulates the use of paper flight strips by air traffic controllers, merging them with the digital world. Users interact with a tablet and touch sensitive screen to annotate and obtain data from the flight strips.

*Paper Augmented Digital Documents* [3] are digital documents that are modified on a computer screen or on paper. Digital copies of a document are maintained in a central database and if needed, printed to paper using IR transparent ink. This is used to track annotations to documents using a special pen.

*Insight Lab* [8] is an immersive environment that seamlessly supports collaboration and creation of design requirement documents. Paper documents and whiteboards allow group members to sketch, annotate, and share work. The system uses bar code scanners to maintain the link between paper, whiteboard printouts, and digital information.

Due to space limitations we limit our review: other systems exist that link the digital and physical world through paper. Examples include *Freestyle* [9], *Designers' Outpost* [7], *Collaborage* [11], and *Xax* [5]. One feature common to prior work in this area is the restriction of the use of physical paper to a flat surface. In *PaperWindows*, we use as many of the three dimensional affordances of physical paper as possible.

### Electronic Books

*XLibris* [16] uses a tablet display and paper-like interface to include the affordances of paper while reading. Users can read a scanned image of a page and annotate it with digital ink. Annotations are captured and used to organize information. Scrolling has been removed from the system:



Figure 2. PaperWindows prototype with three pages.

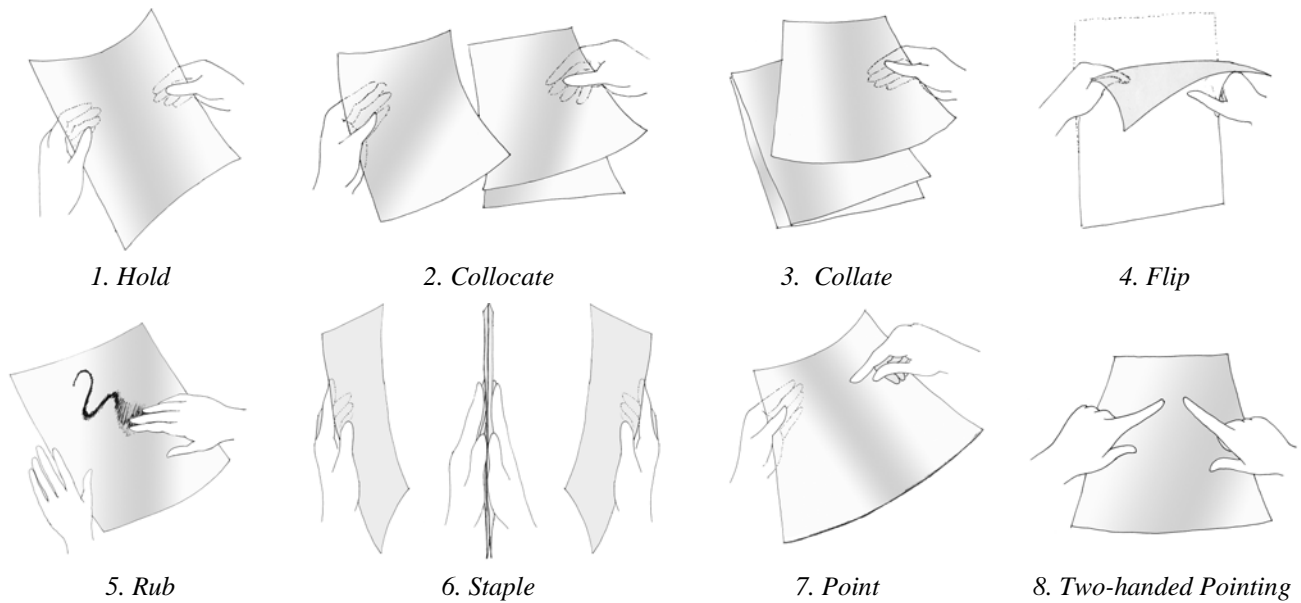
pages are turned using a pressure sensor on the tablet. Users can also examine a thumbnail overview to select pages. Pages can be navigated by locating similar annotations across multiple documents. Fishkin et al. [2] describe embodied user interfaces that allow users to use physical gestures like page turning, card flipping, and pen annotation for interacting with documents. The system uses physical sensors to recognize these gestures. In *PaperWindows*, we draw on these design concepts to establish paper-based interactions modeled on the user's physical gestures.

## THE PAPERWINDOWS CONCEPT

Ideally, *PaperWindows* consists of a number of paper-size flexible displays that interface to a computer system. These flexible displays would offer a high-resolution view of digital documents through a wireless connection, with flexibility similar to that of paper.

Position and shape of these displays could be adjusted for various tasks: paper displays can be spread about the desk, organized in stacks, or held close for a detailed view. Direct manipulation takes place with the paper display itself: by selecting and pointing using the fingers, or with a digital pen. Paper displays could also be used globally within the context of a work environment. For example, users can share content by copying a page and physically handing it to another user.

To test the utility of a set of interaction techniques for digital paper, we have developed a prototype that simulates paper displays. This is achieved by augmenting real paper with Infra Red (IR) reflective markers that are tracked using a Vicon Motion Capturing System [20]. An overhead projector is used to display computer windows on the paper document. Since the Vicon senses the paper's shape, window projection on the paper is automatically corrected for any skew. The *PaperWindows* prototype is shown in Figure 2, with three documents. It presents a scenario where two paper windows are spread over a desk in the periphery of vision, while the user is holding the active document.



**Figure 3. The basic gesture set of PaperWindows.**

#### INTERACTION STYLES

Our PaperWindows interaction grammar was motivated by the natural manipulation of paper. Figure 3 shows the set of gestures used, which include *hold*, *collocate*, *collate*, *flip*, *rub*, *staple*, *point* and *two-handed pointing*. These following gestures provide the basic units of interaction with the system:

1. *Hold*. Users can hold a paper window with one or two hands during use. The currently held paper window is the active document.
2. *Collocate*. This gesture reflects the use of spatial arrangement of paper in the user's workspace. Users can spread paper windows around throughout the tracked environment, and can use this to move less important documents to the periphery of their attention [12].
3. *Collate*. This gesture is used to stack documents, for example, to organize them in piles on a desk. This reduces clutter in the workspace.
4. *Flip*. In single page documents, users can flip a paper window in order to scroll through its pages. In multi-page documents, flipping is used to navigate to the next page of the document.
5. *Rub*. The rubbing gesture allows users to transfer content between paper windows, and between a paper window and a computing peripheral. Like the rubbing gesture in Sun's Starfire video [19], it blends copying and pasting of content into one action.
6. *Staple*. Like a physical staple linking a set of pages, the staple gesture in PaperWindows is used to link two different viewports into the same document. To perform the gesture, users impact a source paper window with a

blank paper window held by the other hand. This clones the source document.

7. *Point*. Users can point at the content of a paper window using their fingers or a digital pen. Fingers and pens are tracked by augmenting them with a minimum of 3 IR reflective markers. By tracking the position of the finger in three-space, the PaperWindows system can identify not only what item the user points at, but also when to issue a click. A single click is performed by tapping the paper window once. A double click is issued by tapping the paper window twice in succession.
8. *Two-handed Pointing*: Two-handed pointing allows users to select disjoint items on a single paper window, or across multiple paper windows.

#### Interaction Techniques

Our set of interaction techniques for paper windows was based on those commonly found in GUIs. We designed 10 techniques for accomplishing basic tasks using our gesture set:

##### 1) Activate

In GUIs, the active document is selected for editing by clicking on its corresponding window. In PaperWindows, the hold gesture is used for this purpose. The currently active paper window remains selected until another paper window is picked up by the user. Although this technique seems quite natural, it may be problematic when using an input device such as the keyboard. For example, a user may be reading from one paper window while typing in another paper window. To address this concern, users can bind their keyboard to the active window using a function key. This is indicated on the paper window through a keyboard icon placed on the top of the page.



Figure 4. An image is opened by tapping on it.

## 2) Select

Items on a paper window can be selected through a one-handed or two-handed pointing gesture. Figure 4 shows how the user opens an item on a page for detailed inspection by pointing at it, and tapping it twice. Two-handed pointing allows parallel use of the hands to select disjoint items on a page. For example, sets of icons can be grouped quickly by placing one finger on the first icon in the set and then tapping one or more icons with the index finger of the other hand. Typically, paper windows are placed on a flat surface when performing this gesture. Two-handed pointing can also be used to select items using rubber banding. With this technique, any items within the rubber band, bounded by the location of the two finger tips, are selected upon release.

## 3) Copy & Paste

In GUIs, copying and pasting of information is typically performed using four discrete steps: (1) specifying the source, (2) issuing the copy, (3) specifying the destination of the paste and (4) issuing the paste. In PaperWindows, these actions are merged into simple rubbing gestures:

1) *Transfer to PaperWindows.* Figure 1 shows how computer windows can be transferred to a paper window by rubbing a blank paper window onto the computer screen. The window content is transferred to the paper window upon peeling the paper window off the screen. The process is reversed when transferring a document displayed on a paper window back to the desktop environment.

2) *Copy Between Documents.* Figure 5 shows how users can copy content from one paper window to the next. This is achieved by placing a paper window on top of a blank page. The content of the source page is transferred by rubbing it onto the blank page. If prior selections exist on the source page, only highlighted items are transferred.

## 4) Scroll

Users can scroll through paper windows in discrete units, or pages. Scrolling action is initiated by flipping the paper window around its horizontal axis. This causes the next page in the active document to be displayed on the back of the paper. Users can scroll back by reversing the flip.

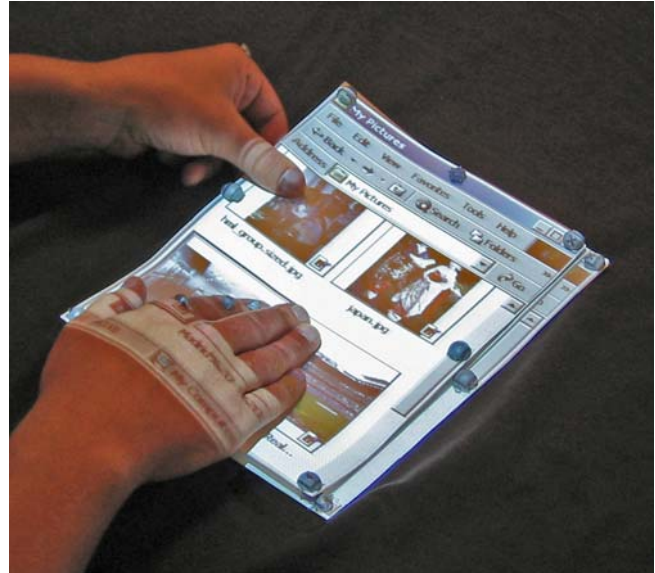


Figure 5. A paper window is placed on top of a blank page and its content is copied using a rubbing gesture.

## 5) Browse

In PaperWindows, flips around the vertical axis are used to specify back and forward actions that are application specific. For example, when browsing the web, a left flip causes the previous page to be loaded. To return to the current page, users issue a right flip. The use of spatially orthogonal flips allows users to scroll and navigate a document independently.

## 6) Views

In PaperWindows, the staple gesture is used to generate parallel views of a window. Users can open a new view into the same document space by stapling a blank page to a source document. This allows users to edit disjoint parts of the document simultaneously using two separate paper windows. Alternatively, users can display multiple pages in a document simultaneously by placing a blank page beside a source document. Rubbing across the pages causes the system to display the next page of the source document on the blank paper window.

## 7) Annotate

The increasing use of stylus-based systems (Tablet PCs) demonstrates the importance of supporting pen-based annotation. In PaperWindows, we employ pen tools augmented with IR markers to annotate directly onto the paper window (see Figure 6). PaperWindows supports the use of differently colored pens through special markers placed on the shaft of the pen.

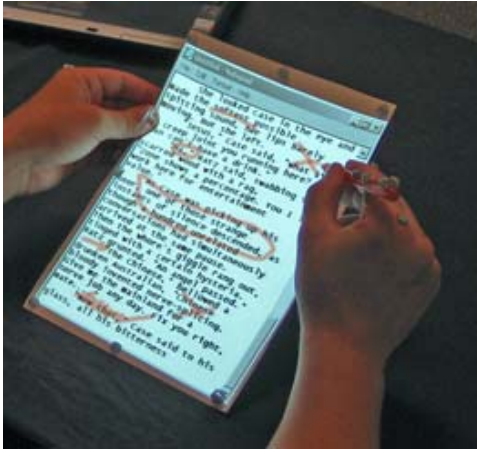


Figure 6. Pages are annotated using an augmented pen.

### 8) Size

Documents projected on a paper window can be scaled using one of two techniques. Firstly, the content of a paper window can be zoomed within the document. Secondly, users can transfer the source material to a paper window with a larger page format. This is achieved by rubbing the source paper window onto a larger paper window. Upon transfer, the content automatically resizes to fit the larger format (see Figure 7).

### 9) Share

Collocated users often share information by emailing or printing out documents. PaperWindows supports informal sharing of physical paper windows between users. We implemented two ways of sharing: slave and copy. When slaving a document, a user staples the source onto a blank paper window. This offers a group member a document that remains linked to the source. In the second technique, the source is copied to a blank paper window using the rubbing gesture, then handed to the group member.

### 10) Open, Save, & Close

*Open.* Users can also use paper windows as digital stationary. Stationary pages are blank paper windows that display a set of application icons prior to use. Users can open a new document by tapping an application icon.

*Save.* A document is saved by performing the rubbing gesture on a single paper window.

*Close.* A paper window is closed by transferring its contents to a desktop computer using a rubbing gesture. Although we do not envision its use with digital displays, our system supports a gesture for deleting a document by crumpling its paper window. This places the corresponding file in the recycle bin of the computer.



Figure 7. Information is magnified by copying it to a paper window with a larger page format.

### APPLICATION SCENARIO – PHOTO COLLAGE

There are many usage scenarios that would benefit from the functionality provided by PaperWindows. One of its key strengths is the use of multiple displays for parallel activities. One such task is the selection of photos for printout from a digital photo database containing raw footage. Our design was inspired by the use of contact sheets by professional photographers. Figure 8 shows how users can compose a photo collage using two paper windows and a rubbing gesture. This scenario shows the use of paper windows as a focus + context technique, with the right hand window providing a thumbnail overview of the database, and the left hand window offering a more detailed view. Users can select thumbnails by pointing at the source page. Thumbnails that appear rotated can be turned using a simple pivoting action of the index finger. After selection, thumbnails are transferred to the collage page (shown on top of Figure 8) through a rubbing gesture. After the copy, thumbnails resize to fit the collage page. When done, the collage page can be printed by rubbing its paper window onto a color printer augmented with IR tags.

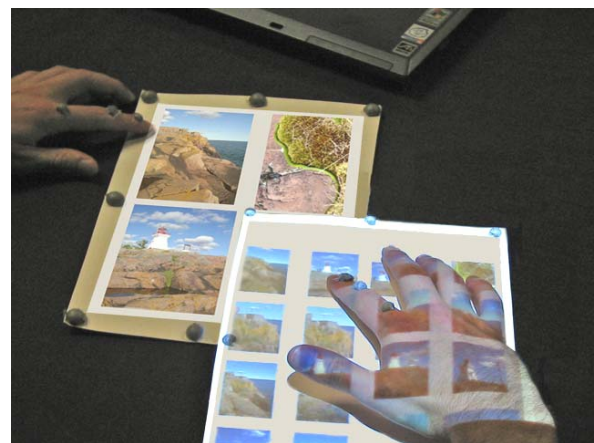


Figure 8. The rubbing gesture is used to generate a photo collage.

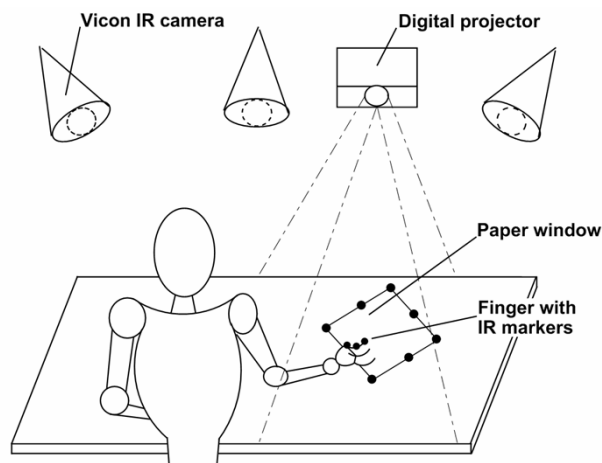


Figure 9. PaperWindows system overview.

The rich set of gestures supported by PaperWindows can also be used to edit photos prior to selection. For example, photos can be cropped by selecting part of the image with a two-handed gesture, and then rubbing the selection onto a collage page. Photos can be enlarged by rubbing them onto a larger sheet of paper.

#### IMPLEMENTATION

An overview of the PaperWindows setup is provided in Figure 9. It includes paper documents augmented with infrared (IR) reflective markers, a user with her finger augmented with IR markers, a digital projection unit, and the Vicon Motion Capturing cameras. The following section discusses each item, illustrating its relationship to other objects in the system.

#### Vicon Motion Capturing System

The Vicon Motion Capturing System [20] is a state-of-the-art computer vision system that is used to capture three dimensional motion data. Our setup consists of 12 cameras that surround the user's work environment, capturing 3D movement of all markers within a workspace of 20'x10'. PaperWindows uses the Vicon data to reconstruct a three dimensional representation of each page.

An initial process of modeling the paper is required before successfully obtaining the marker data. First, a Range of Motion (ROM) trial is captured that describes typical movements of the paper through the environment. This data is used to reconstruct a three dimensional model that represents the paper document. Vicon software calibrates the ROM trial to the model and uses it to understand the movements of paper during a real-time capture. To obtain marker data, we modified sample code that is available as part of Vicon's Real Time Development Kit [20]. The Vicon server streams marker data over a TCP/IP connection with no perceivable latency.

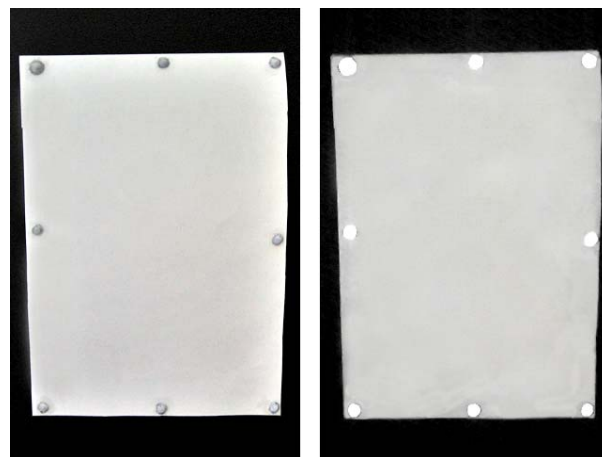


Figure 10. Paper window. The paper as it appears to a user (left), and to the Vicon in infrared (right).

#### IR Augmented Paper & Graphics

Each paper window within the workspace is augmented with IR reflective markers that form an eight point grid (see Figure 10). The Vicon captures the shape of the paper as it is manipulated by the user. A graphics engine written in C++ interfaces with the Vicon server and streams marker data to the PaperWindows application. The engine polls all eight-point page grids, constructing an OpenGL model for each page. The center point of a paper window is determined by averaging between the markers on a page. Bezier curve analysis of marker locations is used to construct a fluid model of the page's shape. All application windows run on an associated Windows PC. Windows that are transferred to a paper window are rendered off-screen into the OpenGL graphics engine. The graphics engine performs real-time screen captures, and maps the window image to the model. The digital projector then displays an inverse camera view onto the page. This allows the system to correct for any skew caused by the shape of the page. The graphics engine also listens to the Vicon connection for input from the keyboard, fingers, or pen. It posts this information to the off-screen window for display. Typically, delays in rendering are minimal. However, for rapid motions (e.g. spinning a paper document) delays are visible and tend to be approximately fifty milliseconds. The rendering latency is largely tied to the power of the graphics card, an ATI Radeon 9800 Pro.

#### Augmented Pens

The fingers of the user are tracked by augmenting them with 3 IR reflective markers. Sensors are placed evenly from the tip of the finger up to the base knuckle. Pens are tracked similarly throughout the environment. The intersection of a finger or pen with a page is calculated using planar geometry. When the pen or finger is sufficiently close, its tip is projected onto the plane of the paper. The position of the tip is related to the length and width of the paper. The x and y position of the point on the plane is calculated using simple trigonometry. When the pen or finger touches the page, the input device is engaged.

### Digital Projector

Windows are rendered onto the paper by a digital projector positioned above the workspace. The projector is placed such that it allows a clear line of sight with the paper between zero and forty-five degrees of visual angle. This is typically sufficient for reading activities, as users tend to position paper pages at angles between twenty-five and forty-five degrees relative to the surface [12]. It also supports writing activity, which typically takes place within a range of zero to fifteen degrees. The PaperWindows system is currently limited by the resolution of a single projector. Using one projector introduces a set of tradeoffs. For example, positioning the projector close to the scene improves the image quality but reduces the overall usable space, and vice versa. An adequate projector position was obtained experimentally. The projector is placed overhead at roughly a meter and a half from the desk. To provide adequate resolution at this distance, desktop windows were scaled down to increase visibility when mapping to paper. Ideally, a set of projectors is used to render the page as it travels throughout the environment of the user.

Initially, a calibration procedure is required to pair the physical position of the paper and the digital output of the projector. This is accomplished by adjusting the position, rotation, and size of the projector output until it matches the dimension of the physical paper. Skew is handled by sampling the paper at various angles from the desk and recording the rotations and translations that correct for it. At the end of the calibration, each value is saved and incorporated into the model for subsequent trials.

### Motion Analysis

Understanding the physical motion of paper and other objects in the system requires a combination of approaches. For gestures like stapling, it is relatively easy to recognize when two pages are held in a different hand and brought close together. However, flipping requires knowledge of a paper's prior state. To recognize this event, the z location of markers at the top and bottom of the page is tracked. During a vertical or horizontal half-rotation, the relative location on the z dimension is exchanged between markers. The movement of the markers is compared to their previous position to determine the direction of the flip.

To detect more advanced gestures, like rubbing, marker data is recorded over multiple trials and then isolated in the data. Once located, an average standard deviation and error is calculated for each component of the finger tip's movement. The system uses these predetermined values to normalize the finger's marker data and recognize the gesture. If such motion occurs near a paper or monitor, a rubbing event is issued.

All methods are dependent on the quality of the data produced by the Vicon. During operation of the Vicon, sensors can be occluded or dropped from the scene if the camera does not have an adequate view of the paper document. Even though the Vicon will recover the lost

sensor, it may not place it back in the same position. For example, if the tip of finger is occluded at any point, the Vicon may think the top knuckle sensor is in fact the tip when it returns within view. To minimize this, the Vicon cameras should be arranged such that there is coverage of the workspace for a full 360 degrees.

### INITIAL USER EXPERIENCE

Initial experiences with the system were encouraging. Five users interacted with a set of paper windows, exploring the gesture set and each of the available interaction techniques. We were particularly interested in observing the users' response to our basic set of actions, such as the use of page flipping for scrolling or navigation, or the use of rubbing and stapling to copy a page.

After an initial explanation, users were given a brief demonstration of the PaperWindows gesture set. In most cases, users were capable of successfully transferring their existing knowledge of paper interactions to the system.

Many users commented that scrolling action seemed to require less effort with PaperWindows than on a PC, even though the extent of physical motion was greater. One possible explanation for this is that the act of flipping a page is such a direct physical correlate for the act of scrolling that it requires little to no mental effort to complete, as compared to the use of a computer input device mapped to a graphical user interface. Another possible explanation offered by some users is that the affordances of paper enhanced their belief that the underlying computing system was reliable and simple. Additionally, the responsiveness of the paper model display indicated at all times to the users that the system was active and able to process their actions. During the browsing task, one user felt as though he was interacting with a 'digital brochure' and not a Web browser.

With regards to stapling and rubbing actions, users felt that the action of bringing two pages together was reliable, immediate and simple to grasp. In general, it seemed our basic gesture set followed the user's need for "how-it-works" knowledge of the system. When dealing with copies of paper windows, several users commented that the ability to collate and collocate documents within their workspace appeared to free them from having to actively keep track of their windowing space, compared to a cluttered single-monitor GUI.

Comments on finger pointing were mixed. In almost all cases, users disliked having to attach sensors to their index fingers. Most users preferred using the stylus for this reason.

### CONCLUSIONS

In this paper, we presented PaperWindows, a prototype windowing environment that simulates the use of digital paper displays. By projecting windows on physical paper, PaperWindows allows us to capture the physical affordances of paper in a digital world. The system uses



paper as an input device by tracking its motion and shape using a Vicon Motion Capturing System. PaperWindows also tracks the movement of pens, fingers, hands and other objects in relation to the context provided by the paper artifact. Users can place a window on a piece of paper by rubbing and pulling it off of an LCD display. Once transferred, paper windows can be held, laid out, and arranged freely to suit the task. Users can interact with the paper document using their hands, fingers, pen, or a set of gestures. We discussed the design of a number of novel interaction techniques for manipulating information with paper windows. To copy a page to another piece of paper, users can use rubbing or stenciling gestures. To navigate pages, a flipping gesture is used. To provide overviews of larger documents users place multiple pages contiguously in space, or use a larger page. Initial user feedback was promising and may suggest that the use of paper windows could lower mental effort required for scrolling, organizing and navigating digital documents.

## REFERENCES

1. Balakrishnan, R., G. Fitzmaurice, G. Kurtenbach and Singh, K. Exploring Interactive Curve and Surface Manipulation Using a Bend and Twist Sensitive Input Strip. In *Proceedings of the 1999 Symposium on Interactive 3D graphics*, ACM Press, 1999, pp. 111-118.
2. Fishkin, K., Gujar, A., Harrison, B., Moran, T. and Want, R. Embodied User Interfaces for Really Direct Manipulation. In *Communications of the ACM*, v.43 n.9, 2000, pp.74-80.
3. Guimbretière, F. Paper Augmented Digital Documents. In *Proceedings of UIST 2003*. Vancouver: ACM Press, 2003, pp. 51-60.
4. Ishii, H. and Ullmer, B. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proceedings of CHI 1997*. Atlanta: ACM, 1997, pp. 234-241.
5. Johnson, W., Jellinek, H., Klotz, L., Rao, R. and Card S. Bridging the Paper and Electronic Worlds: The Paper User Interface. In *Proceedings of the INTERCHI 1993*. Amsterdam: ACM Press, 1993, pp. 507-512.
6. Ju, W. Bonanni, L., Fletcher, R., et al. Origami Desk: Integrating Technological Innovation and Human-centric Design. In *Proceedings of DIS 2002*. London: ACM Press, 2002, pp. 399-405.
7. Klemmer, S., Newman, M., Farrell, R., Bilezikjian, M. and Landay, J. The Designers' Outpost: A Tangible Interface for Collaborative Web Site Design. In *Proc. of UIST 2001*. Orlando: ACM Press, 2001, pp. 1-10.
8. Lange, B., Jones, M., and Meyers, J. Insight Lab: An Immersive Team Environment Linking Paper Displays and Data. In *Proceedings of CHI 1998*. Los Angeles: ACM Press, 1998, pp. 550-557.
9. Levine, S.R. and S.F. Ehrlich. The Freestyle System: A Design Perspective. In *Human-Machine Interactive Systems*, A. Klinger, Editor, 1991, pp. 3-21.
10. Mackay, W.E. & Fayard, A-L. Designing Interactive Paper: Lessons from Three Augmented Reality Projects. In *Proceedings of IWAR'98, International Workshop on Augmented Reality*. Natick, MA: A K Peters, Ltd., 1998.
11. Moran, T., Saund, E., Van Melle, W., Gujar, A., Fishkin, K. and Harrison, B. Design and Technology for Collaborage: Collaborative Collages of Information on Physical Walls. In *Proceedings of UIST 1999*. Asheville, North Carolina: ACM Press, 1999, pp. 197-206.
12. O'Hara, K. and Sellen, A. A Comparison of Reading Paper and On-line Documents. In *Proceedings of CHI 1997*. Atlanta: ACM Press, 1997, pp. 335-342.
13. Philips OLED Technology. <http://www.business-sites.philips.com/mds/section-1131/>
14. Rekimoto, J. Pick-and-Drop: A Direct Manipulation Technique for Multiple Computer Environments. In *Proceedings of UIST 1997*. Banff: ACM Press, 1997, pp. 31-39.
15. Rekimoto, J. SmartSkin: An Infrastructure for Freehand Manipulation on Interactive Surfaces. In *Proceedings of CHI 2002*. Minneapolis: ACM Press, 2002, pp. 113-120.
16. Schilit, B., Golovchinsky, G., and Price, M. Beyond Paper: Supporting Active Reading with Free Form Digital Ink Annotations. In *Proceedings of CHI 1998*. Los Angeles: ACM Press, 1998, pp. 249-256.
17. Schwesig, C., Poupyrev, I., and Mori, E. Gummi: A Bendable Computer. In *Proceedings of CHI 2004*. Vienna: ACM Press, 2003, pp. 263-270.
18. Sellen, A., and Harper, R. *The Myth of the Paperless Office*, MIT Press, Cambridge, MA, 2003.
19. Sun Starfire: A Video of Future Computing. <http://www.asktog.com/starfire/starfirescript.html>.
20. Vicon. <http://www.vicon.com>.
21. Weiser, M. The Computer for the 21st Century. *Scientific American*, 1991, 265 (3), pp. 94-104.
22. Wellner, P. The DigitalDesk Calculator: Tangible Manipulation on a Desk Top Display. In *Proceedings of UIST 1991*. Hilton Head: ACM Press, 1991, pp. 27-33.