PaperTab: An Electronic Paper Computer with Multiple Large Flexible Electrophoretic Displays

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CHI 2013 Extended Abstracts, April 27–May 2, 2013, Paris, France.
ACM 978-1-4503-1952-2/13/04.

Abstract
We present PaperTab, a paper computer with multiple 10.7" functional touch sensitive flexible electrophoretic displays. PaperTab merges the benefits of working with electronic documents with the tangibility of paper documents. In PaperTab, each document window is represented as a physical, functional, flexible e-paper screen called a displaywindow. Each displaywindow is an Android computer that can show documents at varying resolutions. The location of displaywindows is tracked on the desk using an electro-magnetic tracker. This allows for context-aware operations between displaywindows. Touch and bend sensors in each displaywindow allow users to navigate content.

Author Keywords
Flexible Display Interfaces; Organic User Interfaces.

ACM Classification Keywords
H.5.m [Information Interfaces and Presentation]: Miscellaneous.

General Terms
Human Factors.

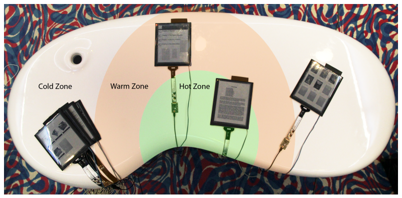

Figure 1. PaperTab desk with 9 physical windows and (virtual) hot, warm and cold zones.

Introduction

The vision of a physical desktop computing system based on the way office workers use paper documents has been an enduring research goal [2]. One of the reasons for the longevity of paper, according to Sellen and Harper [11], is that it provides tactile-kinesthetic feedback when organizing and navigating information that is not available in traditional digital windowing environments. Paper, as a physical medium, is also thin, lightweight and portable. It provides 3D spatial organization of information, while enabling concurrent access to multiple streams of information [11]. Graphical User Interfaces (GUIs) provide superior opportunities for on-the-fly electronic manipulation and updating of information over paper. In this work, we address three major limitations of the GUI, as compared to paper documents: (1) users are severely restricted in the way they concurrently manipulate and organize multiple windows; (2) spatial manipulation of windows is limited by screen size and (3) users cannot apply spatial memorization skills for GUI-based document retrieval as effectively as they can in real, physical, environments [5]. The emerging technology of thin-film flexible displays [6] presents an opportunity to merge the physical world of paper with the digital world of information via Organic User Interfaces [12]: non-flat, flexible, tactile, high-resolution display interfaces. Flexible displays are sufficiently thin to approximate paper-like interactions, and sufficiently light to allow for efficient spatial interactions between displays. While research on flexible display interfaces has pursued the embodiment of digital data on paper [5], [6], this research has mostly focused on the usability of *single* and *small* display interactions. In this paper, we extend this work to multi-display large format interactions. In PaperTab, each graphical window is represented by a fully functional, paper-sized 10.7” diagonal Plastic Logic thin-film high-resolution flexible electrophoretic display [8].

Background

DigitalDesk [13] was one of the first physical paper computers. It seamlessly merged interactions between physical paper and digital documents on a physical desk. Users were able to select data from paper documents and copy it into digital documents. In PaperWindows, Holman et al. [5] created a windowing environment that simulated fully wireless, full-color digital paper. Holman projected digital documents on physical paper, allowing for input and output directly on the flexible display. PaperWindows demonstrated use of gestural inputs such as hold, collate, flip and bend. Similarly, Lee et al. [7] used image projection on foldable materials to simulate flexible displays with variable form factors and dimensions. None of these systems deployed functioning thin-film electronic paper displays. Research in thin-film display interactions started with paper mockups, bendable substrates on rigid devices and projected flexible displays [5], [10]. With the recent availability of working flexible displays, projects like PaperPhone [6] explored new interaction techniques such as bending as an interaction paradigm. DisplayStacks [4] is one of the few papers to explore interaction techniques for stacking multiple functional E Ink displays. However, it featured only a small set of smartphone sized displays, and presented a limited set of interactions between screens based on stacking metaphors.

Interaction Techniques

Figure 1 shows the PaperTab desk with three zones of proximity to the user, each pertaining to a different

Figure 2. Pointing with a hot display (right) into a warm display, in this case showing a TOC (left), displays detailed focus information on the hot display, in this case a book page.

focus level: *hot* (within arm's reach, active document), *warm* (at arm's reach, locked or stacked document), and *cold* (outside arms reach, filed document).

In the hot zone, displaywindows are either held by the user, or within immediate hand's reach of the user. They contain full-screen documents editable by the user via touch input or keyboard. Displaywindows remain hot until the user releases them in a warm or cold zone.
In the warm zone, displaywindows are at arm's reach of the user. They are the equivalent of minimized windows, or windows stacked below the top window in a GUI. When a hot displaywindow is moved to the warm zone, this causes the displaywindow to show the thumbnail overview of its document. For example, if the user is browsing a full screen photo in an album,

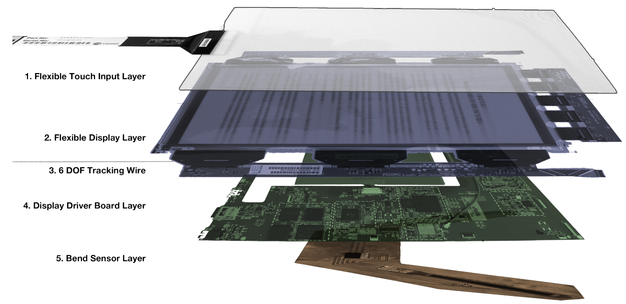

Figure 3. Exploded view of a displaywindow.

moving the display into the warm zone would cause it to display thumbnails of all photos in the album.
In the cold zone, displaywindows are just outside of arm's reach of the user, yet easily accessible by leaning or reaching forward over the desk. Cold displaywindows allow storage of documents out of the way of the active task. They are equivalent to *file folders* in GUI filing systems.

Focus+Context Interactions
Figure 2 shows how multi-display interactions provide focus+context navigation of content on displaywindows. When a user points the top left corner of the hot displaywindow onto the thumbnail on the underlying warm or cold displaywindow, the hot displaywindow shows a full screen preview of the thumbnail. After previewing the item, the user can move it permanently onto the hot displaywindow by lifting it and pulling it into the hot zone [9]. Document files are opened by pointing an empty displaywindow at a list of document file icons represented on a cold zone folder.

Implementation
Figure 3 shows an exploded view of a displaywindow

consisting of 6 flexible and semi-flexible layers. Each displaywindow is approximately 3 *mm* thick and weighs approximately 70 *g*. Each displaywindow is a fully functional Android computer that only communicates with a host PC for input and to coordinate data exchanges with other displaywindows. The first layer consists of a flexible, thin-film, transparent Zytronic capacitive touch screen [14], 10.7" in size diagonally. This layer is connected to a host PC with a ribbon cable. The second layer features a large 10.7" diagonal flexible Plastic Logic electrophoretic display with a minimal bezel that was custom manufactured for the PaperTab system. The display features a resolution of 1280 *x* 960 pixels, with a *full-screen* refresh rate of 200 *ms*. An electro-magnetic sensor mounted on each displaywindow allows tracking of location and orientation relative to the other displaywindows, as well as the desk and the user. It consists of a small trakSTAR sensor probe that is attached via a wire to a processor box placed underneath the desk [1].
The fourth layer features a Plastic Logic *Apollo* board [8] running Android and featuring an 800 MHz ARM Cortex-A8 processor, full graphics subsystem as well as a Wi-Fi connection. Although elements of the Apollo board are rigid, a modular mounting strategy allows flexing of the entire display surface. This layer also contains a flexible lithium-polymer battery that powers both display and driver board. The bend sensitive layer consists of 2 bi-directional FlexPoint [3] bend sensors mounted on a custom-built flexible circuit board mounted directly underneath the display driver board. Bend sensors are connected via a flat ribbon cable to an Arduino Mega 2560 prototyping board that communicates with the host PC for processing bends. Displaywindows are tethered to a host PC, an 8-Core MacPro running Windows 7 that is placed underneath the desk. It processes all input from the touch layer, 6 DOF tracker, and bend sensor. It also handles communication between displaywindows, e.g., in case of co-location or focus+context pointing.

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