PaperFold: A Shape Changing Mobile Device with Multiple Reconfigurable Electrophoretic Magnetic Display Tiles

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Abstract
We present PaperFold, a novel shape changing mobile device with multiple reconfigurable touch sensitive thin-film electrophoretic magnetic display tiles. PaperFold explores the perceived benefits of having multiple computing devices combined into a single mobile device featuring multiple detachable displays. In PaperFold, each display tile can act independently or as part of a single system. Advantages include better support for performing tasks that traditionally require multiple devices, as well as physical manipulation and sharing of views. Touch and Inertial Measurement Unit (IMU) sensors embedded in each display tile allow users to dynamically manipulate content.

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

General Terms
Human Factors; Organic User Interfaces; Flexible Displays; Foldable User Interfaces.

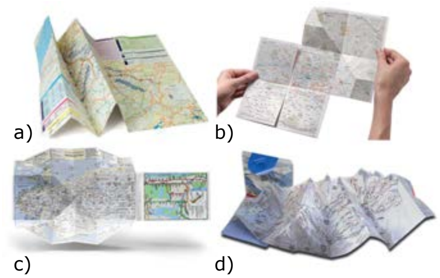

Figure 1. Modulating screen real estate: a) Rectangular map; b) Zoomable rectangular map; c) 2D popout map; d) 3D topographical popout map.

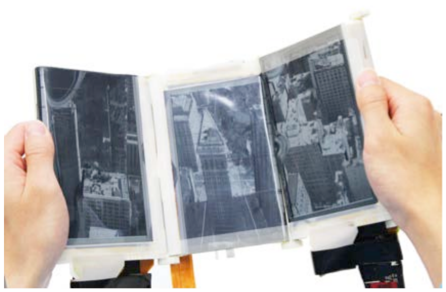

Figure 2. PaperFold prototype with 3 display segments.

Introduction

Despite increases in display resolution, mobile devices have displays that are fixed and limited in size. Consequently, multiple documents or apps are typically accessed in sequence rather than in parallel. On mobile devices, navigating large single documents requires sequential navigation, e.g., by scrolling or zooming, allowing little contextual overview. By contrast, paper documents can be folded, detached or combined into multiple, smaller elements. Such properties allow paper documents to be navigated and organized in larger spaces, allowing concurrent access to multiple documents [12]. Paper also has great properties for mobility: it is physical, thin and lightweight. As such, the development of electronic paper computers that adopt certain qualities or metaphors of interacting with paper documents has been an enduring research goal [1][9][12]. A number of paper metaphors can be used as inspiration to the design of mobile devices that, like paper, allow for multiple display segments that can be folded into smaller form factors. Books use folding as both a navigational and space saving technique. Paper maps have malleable display sizes. Figure 1 shows four types of paper map folding techniques: a) a traditional map folded along rectangular creases; b) a rectangular map with different levels of zoom; c) a popout map that folds out into a polygonal mesh, which only functions to rapidly modulate display size; d) a popout map that uses a polygon mesh to provide 3D topographical information on a mountain range.

PaperFold (Figure 2) investigates how thin-film, paper-like electrophoretic mobile devices [5][6][10][14] might adopt dynamic modulation of screen real estate through folding and tearing techniques.

Background

Current solutions exploring book form factors, often involve rigid dual-screen form factors that can orient around one axis. [4][13] Chen et al. [2] discussed an e-book reader featuring two displays mounted on separate slates that can be used in side-by-side or detached configurations, supporting navigation techniques like folding, flipping, and fanning. Chen et al. [3] also evaluated a multi-slate reading system, aimed at understanding how increased screen real estate across multiple devices can enhance navigation and interaction techniques in reading activities. Hinckley et al. [7] explored the use of tablet PCs for spanning contiguous images across multiple display surfaces. The system was capable of performing simple view operations such as collating two displays, or full screening an image across two displays. Codex [8] featured a dual-screen tablet computer, detachable and reconfigurable into various form factors. Codex can be oriented in a variety of postures to support individual work, ambient display, or collaboration with another user. The authors demonstrate interaction techniques supporting division of labor for tasks across displays.

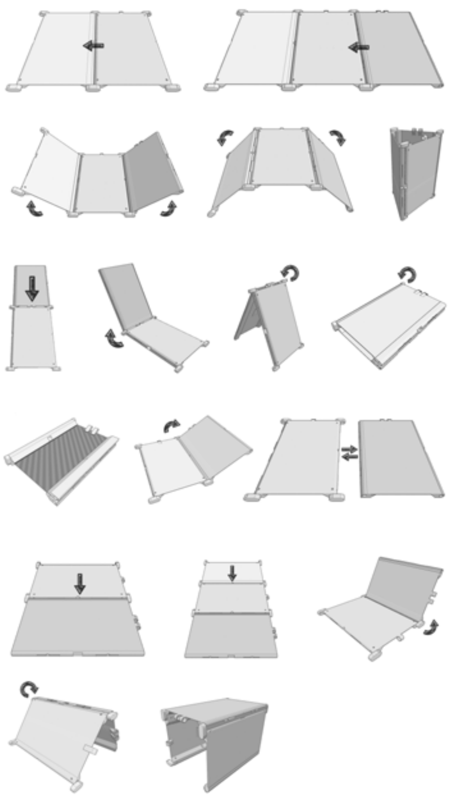

Figure 3. Most frequently performed shape changes with PaperFold prototype in our participatory design session

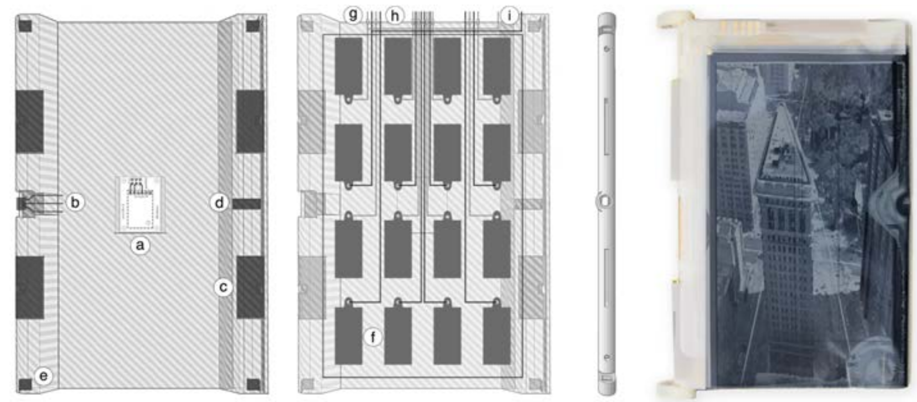

Figure 4: View of the component layers of a single PaperFold panel. (a) IMU Board. (b) Linear Hall Effect Sensor. (c) 1.0 X 3/8 X 1/16” Block magnets. (d) 1/4" X 1/4"Cylindrical Magnet. (e) 1/8" X 1/8"Block Magnets. (f) Copper Substrate (g) 20M Ohm Sensor Pins. (h) 40M Ohm Sensor Pins. (i) Common Send Pins.

PaperFold Configurations

To investigate what would be the most functional shapes of a foldable device, we conducted a participatory design session in which users were asked to create what they thought of as the most useful transformations of shape for a 2-display hinged/detachable device. We then repeated the exercise using 3 displays and 4 displays. For each shape, we asked participants to think of an associated functionality. Figure 3 shows the most common shape changes produced by participants for 2 and 3 display configurations since participants had difficulty relating to the 4 display configurations. In a follow-up experiment, we asked participants to rate the match between the shape changes produced in our participatory study and a list of view operations suggested by participants, which included: *Collate/Extend View*; *Zoom In/Out*; *Show 3D View*; *Show Thumbnails*; *Show Full Screen*; *Show Toolbar; Show Keyboard*; *Show Phone*; *Show Different Application*; *Show Blank View*; *Duplicate View.*

Implementation

PaperFold is a foldable thin-film device with multiple detachable flexible display tiles. Each tile consists of a flexible E Ink display, and a flexible 3D printed substrate with embedded sensors.

Flexible Displays

Each PaperFold panel features a flexible Plastic Logic electrophoretic display [11] thermoformed to the curvature of the magnetic hinge of the 3D printed tiles. Applying a curvature to the edge of the display allow us to replicate the effect of having continuous stream of information between displays. Each display is controlled through a custom Plastic Logic driver board connected to a Mac Mini controlling the logic and interface graphics.

3D Printed Tiles

Figure 4 shows an overview of the back plane of one of PaperFold's tiles. Each tile measures 15x10 *cm* with a thickness of 5 *mm* (Figure 4.3). Tiles were printed in ABS Plastic at a layer resolution of 0.25*mm*. Each tile contains an IMU Board (Figure 4.1.a) and a linear Hall Effect Sensor (Figure 4.1.b) tethered to an Arduino. Magnets embedded in the bezel of the 3D printed substrate (Figure 4.1.c;d;e) allow PaperFold panels to be arbitrarily combined in a variety of configurations. Hall Effect sensors allowing our system to detect distinct connections among various tiles. 9DOF IMUs calculate the absolute orientation of each tile. Using this information, our system is able to calculate the shape configuration, and determine what view operations should occur upon changes to this configuration.

Touch Input

Figure 4.2 shows a custom-built limited resolution multi-touch capacitive touch sensor circuit that is integrated into each tile. To maximize the effectiveness of touch detection, and thus preventing unintended input, each line of our 4 x 4 copper substrate array is connected to components with a distinct electrical resistance. The wiring circuit is connected to the Arduino Board via a digital multiplexer.

Software

A C# application interprets changes in orientation, connection and touch input data reported by each individual tile. It also runs the applications displayed on PaperFold, sending segmented images to the display tiles depending on the configuration of the tiles, as well as user input.

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