ELECTRONIC PAPER COMPUTERS: INTERACTING WITH FLEXIBLE DISPLAYS FOR PHYSICAL MANIPULATION OF DIGITAL INFORMATION

by

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Abstract

Flexible displays are being widely adopted because of their thinness, lightweight and low power-consumption. Current research on flexible displays has focused on various ways of interacting with a single flexible display similar to that of using a mobile phone. The introduction of thin-film flexible displays has enabled us to represent data as a deck of thin and flexible cards or sheets of standard-sized paper. This is largely an unexplored area of research. This manifestation of digital data opens up newer forms of interaction techniques such as stacking, thumbing through, while supporting traditional tabletop interaction techniques such as collocation, shuffling and reordering documents on a desk.

In this thesis, we present multi-display paper computer prototypes that combine the physical properties of paper with the affordances of digital media. We use the physical affordances of flexible displays, i.e., their thinness, low mass, and flexibility, as design elements to create paper computer prototypes that support spatial, tactile, and asymmetric bimanual manipulation of digital information. With Snaplet, we explore how flexibility provides an interaction context for a wearable device that fits the body. With DisplayStacks, we take advantage of the thinness of displays to explore stacking as an interaction metaphor. With PaperTab, we combine these affordances with the low mass of displays to present a physical computing interface that enables 3D spatial organization of information, as well as parallel access to multiple data streams.

We report on a qualitative study to show how PaperTab’s interaction techniques can be easy to learn, without inducing significant physical demands or mental demands. We report results from three Fitts’ law experiments to understand how device mass and rigidity affect interaction efficiency in spatial interactions. We formally define Paper Computers based on our experience developing the prototypes, and our qualitative and quantitative study data.
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Statement of Originality

(Required only for Division IV Ph.D.)

I hereby certify that all of the work described within this thesis is the original work of the author. Any published (or unpublished) ideas and/or techniques from the work of others are fully acknowledged in accordance with the standard referencing practices. Parts of this thesis have been reused from [29, 84–86].

(Aneesh Pradyumna Tarun)

(April, 2017)
# Table of Contents

Abstract ................................................................................................................................. ii
Acknowledgements .................................................................................................................. iii
Statement of Originality .......................................................................................................... v
List of Figures ........................................................................................................................ xii
List of Tables .......................................................................................................................... xv

Chapter 1 Introduction ............................................................................................................ 1
  1.1 Motivation ....................................................................................................................... 4
  1.2 Problem Statement ......................................................................................................... 6
  Thesis Statement .................................................................................................................. 6
  1.3 Terminologies ................................................................................................................ 8
  1.4 Contributions ................................................................................................................. 10
  1.5 Thesis Outline .............................................................................................................. 13

Chapter 2 Literature Review ................................................................................................. 15
  2.1 The Myth of the Paperless Office ................................................................................ 15
  2.2 Bridging Physical and Digital Worlds .......................................................................... 17
  2.3 Paper-like Manipulation of Digital Media .................................................................. 19
    2.3.1 Interaction between multiple displays ................................................................. 21
    2.3.2 Flexible Displays ................................................................................................. 22
  2.4 Spatial Manipulation of Digital Information ............................................................... 23
    2.4.1 Stacking ............................................................................................................... 23
    2.4.2 Collocated Displays ........................................................................................... 25
    2.4.3 Tracking Documents ......................................................................................... 25
  2.5 Evaluating Flexible Display Interactions .................................................................... 27
    2.5.1 Fitts’ Law ......................................................................................................... 28
    2.5.2 Area Cursors ................................................................................................. 30
    2.5.3 Fitts’ Law Evaluation of Tangibles ................................................................... 30
  2.6 Summary .................................................................................................................. 31

Chapter 3 Snaplet: A wearable flexible computer ................................................................. 32
  3.1 Introduction ................................................................................................................. 33
  3.2 Snaplet ..................................................................................................................... 35
  3.3 Design Rationale ........................................................................................................ 36
    3.3.1 Function Equals Form ....................................................................................... 36
5.2 PaperTab .............................................................................................................................. 82
5.3 Design Rationale .................................................................................................................. 82
  5.3.1 Window = 1 Display ....................................................................................................... 83
  5.3.2 Location Awareness ...................................................................................................... 83
  5.3.3 Spatial Proximity = Resolution ..................................................................................... 83
  5.3.4 Spatial Proximity = Focus ............................................................................................. 84
  5.3.5 Movability = Mass and Volume ................................................................................... 84
  5.3.6 Display = Pointing Device ......................................................................................... 85
5.4 Interaction Techniques ......................................................................................................... 85
  5.4.1 Zone Interactions .......................................................................................................... 86
    5.4.1.1 Hot Zone .................................................................................................................. 86
    5.4.1.2 Warm Zone .............................................................................................................. 87
    5.4.1.3 Cold Zone ................................................................................................................. 87
    5.4.1.4 Document Notifications ......................................................................................... 88
  5.4.2 Focus+Context Interactions .......................................................................................... 89
    5.4.2.1 Filing and Opening Documents ............................................................................... 89
    5.4.2.2 Moving Data Objects ............................................................................................. 90
    5.4.2.3 Keyboard Input ....................................................................................................... 91
    5.4.2.4 Bend Interactions ................................................................................................... 91
    5.4.2.5 Colocation of Tabs ................................................................................................ 92
  5.4.3 Summary of Interaction Techniques ............................................................................. 93
5.5 Implementation .................................................................................................................... 93
  5.5.1 Prototype 1: Extending DisplayStacks ............................................................................ 94
  5.5.2 Prototype 2: Large Displays with limited tethering ..................................................... 96
  5.5.3 Final Prototype .............................................................................................................. 97
  5.5.4 Layer 1: Flexible Touch Input ...................................................................................... 98
  5.5.5 Layer 2: Flexible Electrophoretic Display .................................................................... 98
  5.5.6 Layer 3: 6 DOF Location and Orientation Tracking .................................................... 99
    5.5.6.1 Hot, Warm and Cold Zone Tracking ....................................................................... 99
  5.5.7 Layer 4: Bend Sensor Layer .......................................................................................... 100
  5.5.8 Layer 5: Capacitive Grounding Wire (not shown) ....................................................... 100
  5.5.9 Software ...................................................................................................................... 100
    5.5.9.1 Input Threads ......................................................................................................... 101
    5.5.9.2 Interaction Thread .................................................................................................. 101
Chapter 5 Evaluation of Flexible Display Interactions as Area Cursors and Within-display Pointers

5.6 User Study .......................................................................................................................... 102

5.6.1 Participants .................................................................................................................. 102

5.6.2 Task and Procedure ..................................................................................................... 102

5.7 Results ................................................................................................................................ 104

5.7.1 Between-display Interactions ...................................................................................... 105

5.7.2 Within-display Interactions ......................................................................................... 106

5.7.3 Bend Interactions ........................................................................................................ 107

5.8 Discussion .......................................................................................................................... 107

5.8.1 Implications for System Software and Hardware ....................................................... 108

5.9 Summary ............................................................................................................................ 109

Chapter 6 Evaluation of Flexible Display Interactions as Area Cursors and Within-display Pointers

6.1 Introduction ........................................................................................................................ 111

6.1.1 Do Paper Computers Need Flexible Displays? ........................................................... 112

6.1.2 Contribution ................................................................................................................ 113

6.2 Spatial Interactions with Flexible Displays ...................................................................... 114

6.2.1 Flexible Displays as Area Cursors .............................................................................. 115

6.2.2 Flexible Displays as Pointing Devices ........................................................................ 115

6.3 Study 1: Throughput of Between-display Interactions ...................................................... 115

6.3.1 Procedure .................................................................................................................... 116

6.3.2 Measurements ............................................................................................................. 116

6.3.3 Participants .................................................................................................................. 117

6.3.4 Experimental Design and Index of Difficulty ............................................................. 118

6.3.5 Display Factors: Flexibility and Mass ........................................................................ 118

6.3.6 Apparatus .................................................................................................................... 120

6.3.7 Location Measurement Hardware and Software ......................................................... 121

6.3.8 Target Points ............................................................................................................... 122

6.3.9 Analysis: Index of Performance .................................................................................. 123

6.4 Study 1: Results ................................................................................................................. 124

6.4.1 Paper vs. Flexible Display .......................................................................................... 125

6.4.2 Error Rates .................................................................................................................. 125
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.3 Regression Models</td>
<td>125</td>
</tr>
<tr>
<td>6.5 Study 1: Discussion</td>
<td>126</td>
</tr>
<tr>
<td>6.6 Study 2: Throughput of Pointing Within Displays</td>
<td>127</td>
</tr>
<tr>
<td>6.6.1 Procedure</td>
<td>128</td>
</tr>
<tr>
<td>6.6.2 Measurements</td>
<td>128</td>
</tr>
<tr>
<td>6.6.3 Participants</td>
<td>129</td>
</tr>
<tr>
<td>6.6.4 Experimental Design</td>
<td>129</td>
</tr>
<tr>
<td>6.6.5 Apparatus</td>
<td>129</td>
</tr>
<tr>
<td>6.7 Study 2: Results</td>
<td>130</td>
</tr>
<tr>
<td>6.7.1 Error Rates</td>
<td>132</td>
</tr>
<tr>
<td>6.8 Study 2: Discussion</td>
<td>132</td>
</tr>
<tr>
<td>6.9 Study 3: Throughput of Dragging Within Displays</td>
<td>133</td>
</tr>
<tr>
<td>6.9.1 Procedure</td>
<td>133</td>
</tr>
<tr>
<td>6.9.2 Measurements</td>
<td>134</td>
</tr>
<tr>
<td>6.9.3 Participants</td>
<td>134</td>
</tr>
<tr>
<td>6.9.4 Experiment Design</td>
<td>134</td>
</tr>
<tr>
<td>6.10 Study 3: Results</td>
<td>136</td>
</tr>
<tr>
<td>6.10.1 Error Rates</td>
<td>136</td>
</tr>
<tr>
<td>6.11 Study 3: Discussion</td>
<td>136</td>
</tr>
<tr>
<td>6.12 Summary Discussion</td>
<td>137</td>
</tr>
<tr>
<td>6.13 Limitations and Directions</td>
<td>138</td>
</tr>
<tr>
<td>6.14 What is a Paper Computer?</td>
<td>138</td>
</tr>
<tr>
<td>6.15 Summary</td>
<td>139</td>
</tr>
<tr>
<td>Chapter 7 Conclusion and Future Work</td>
<td>141</td>
</tr>
<tr>
<td>7.1 Summary</td>
<td>141</td>
</tr>
<tr>
<td>7.2 Contributions</td>
<td>142</td>
</tr>
<tr>
<td>7.3 Future Work</td>
<td>145</td>
</tr>
<tr>
<td>7.3.1 Untethered displays</td>
<td>145</td>
</tr>
<tr>
<td>7.3.2 Long-term Evaluation</td>
<td>146</td>
</tr>
<tr>
<td>7.3.3 Designing for Appropriation</td>
<td>147</td>
</tr>
<tr>
<td>7.3.4 Different paradigms of interacting with Paper Computers</td>
<td>147</td>
</tr>
<tr>
<td>References</td>
<td>148</td>
</tr>
<tr>
<td>Appendix A: Building Flexible Circuits</td>
<td>164</td>
</tr>
<tr>
<td>Appendix B: Research Proposal Approval Letter</td>
<td>168</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1. Paper provides tactile-kinesthetic feedback and 3D spatial organization of information, while enabling parallel access to multiple streams of information ................................................. 2

Figure 2. Flexible displays allow for the physical manipulation of digital information, resembling paper. DisplayStacks [11] (Left) and PaperTab [32] (Right). .......................................................... 3

Figure 3. Fitts’ Law [23] models the movement of input devices using reciprocal target acquisition tasks in an interaction space. Reprinted from [23] with permission. .......................................................... 29

Figure 4. Fitts [23] modeled the efficiency of moving discs of varying sized holes (left) and that of moving pins of varying weights (right). Reprinted from [23] with permission. .......... 30

Figure 5. Snaplet, a wearable flexible computer. It switches its application context to watch and media player when worn in a convex shape. ............................................................... 32

Figure 6. Snaplet, when held flat, changes to a PDA with pen-based note taking functionality... 34

Figure 7. Bend Gestures: Example of bending a side (left) or a corner (right) ......................... 37

Figure 8. Snaplet consists of (b) 3.7” flexible electrophoretic ink display driven by (a) Broadsheet AM300 kit. Sensors attached to the display communicate via (c) an Arduino Mega microcontroller. .......................................................................................................................... 40

Figure 9. Flexible Display and the Sensor layers. ..................................................................... 43

Figure 10. Flexible displays allow for the physical manipulation of digital information, resembling paper. .......................................................................................................................... 48

Figure 11. Physical configurations of stacked displays, and selected interaction techniques (gray arrows). .......................................................................................................................... 51

Figure 12. Contextual overview of spreadsheet by fanning out displays. ............................ 58

Figure 13. Contextual menu in a book reader by overlapping displays. .............................. 59

Figure 14. Linear browsing of piled information by bending the top display. ...................... 60

Figure 15. Rough prototype (first iteration) consisting of conductive zones (left) and 4×4 grid of conductive dots (right) mounted on foam and cardboard. ....................................................... 65

Figure 16. Final prototype. Detecting relative location of displays using an asymmetric pattern of conductive dots. Front of display (left) and back of display (right). ....................................................... 65

Figure 17. Each display is augmented with 4 layers: a conductive bezel on an FPC, 4 bend sensors on an FPC, a Wacom digitizer, and a conductive dot pattern on an FPC. ......................... 67
Figure 18. A subset of the conductive dots of the top display forms a circuit with a subset of the conductive bezel of the bottom display (both sets illustrated in red.) A fanned occlusion is detected in this example. ................................................................. 69
Figure 19. State machine diagram showing transitions of display states. ........................................ 71
Figure 20. PaperTab with 9 physical windows and (virtual) hot, warm and cold zones. .......... 78
Figure 21. User interacting with a tab—a physical window representing a document. ............. 81
Figure 22. Hot, warm and cold proximity zones in PaperTab .................................................... 85
Figure 23. Pointing with a hot display (right) into a warm display, in this case showing email inbox (left), displays detailed focus information on the hot display, in this case contents of the selected email .................................................................................................................... 88
Figure 24. Application-specific tasks can be triggered by bending the top-left corner of a tab. Here, we see a user bending a tab to send an email response ......................................................... 90
Figure 25. Extending the document view by collocating two tabs. Touch and drag action can be used to transfer content between such tabs ................................................................. 91
Figure 26. PaperTab Prototype 1 (left): extending DisplayStacks. A custom sensor array (right) was used to track the position of displays on a desk........................................................................ 94
Figure 27. PaperTab Prototype 2: Plastic Logic 10.7” display driven by a portable processor and battery ................................................................................................................................. 95
Figure 28. Exploded view of a tab, which is made out of 6 layers: 1) Flexible Touch Layer, 2) Flexible Display, 3) 6 DOF Tracker, 4) Bend Sensor Layer and 5) Capacitive Grounding wire (not shown) ................................................................................................................................. 97
Figure 29. Mean user rating and standard error (s.e.) for interaction techniques in PaperTab.... 104
Figure 30. Different Display conditions. (a) Flexible Low Mass Display (83g); (b) Rigid Low Mass Display (83g); (c) Flexible High Mass Display (661g); (d) Rigid High Mass Display (661g) ........................................................................................................................................... 117
Figure 31. Between-display task: A rigid, low mass display showing 30 mm cursor and target points spaced 150 mm apart illuminated by laser pointers. IR reflective marker attached to the center of the display is visible within the 30 mm cursor ................................................................................................................................. 120
Figure 32. Overview of the experiment setup: (a) Vicon cameras tracking the experiment area with an accuracy of 0.2mm; (b) 8 visible red light laser pointers illuminating the target points; (c) Precisely marked target points illuminated on the desk ................................................................................................................................. 121
Figure 33. Fitts’ Law Experiment 1 (Between-display interactions): Fitts’ Law model for each display type showing movement time (MT, in ms) and effective Index of Difficulty (IDe, in bits). ........................................................................................................................................... 124
Figure 34. Within-display tasks: A flexible low mass display pointing at a 10mm target.Tip of the display has a red cursor and reflective markers (inset). .......................................................... 127
Figure 35. Fitts’ Law Experiment 2 (Within-display Pointing): Fitts’ Law Regression for each device showing movement time ($MT$, in $ms$) and effective index of difficulty ($ID_e$, in $bits$). ..... 131
Figure 36. Structural holds (dotted line indicates increased rigidity) formed with flexible displays. ...................................................................................................................................................... 132
Figure 37. Fitts’ Law Experiment 3 (Within-display Dragging): Fitts’ Law regression for each device comparing movement time ($MT$, in $ms$) with effective index of difficulty ($ID_e$, in $bits$). 135
Figure 38. Interactive Origami Boat made with custom-designed flexible copper circuit. ........ 164
Figure 39. Steps for designing and building custom flexible circuits........................................ 167
List of Tables

Table 1. Bloodhound Flexible Electrophoretic Ink Display Properties........................................... 41
Table 2. Plastic Logic Flexible Electrophoretic Ink Display Properties............................................. 98
Table 3. Fitts’ Law Experiment 1 (Between-display interactions): Mean Effective Index of
Performance (in \textit{bits/s}) and standard error (s.e.) for different display types............................. 123
Table 4. Fitts’ Law Experiment 2 (Within-display Pointing): Mean Effective Index of
Performance (in \textit{bits/s}) and standard error (s.e.) between conditions........................................ 130
Table 5. Fitts’ Law Experiment 3 (Within-display Dragging): Mean Index of Performance (in
\textit{bits/s}) and standard error (s.e.) between conditions................................................................. 135
Chapter 1

Introduction

This chapter is in part based on [29]

Over the past 2000 years, paper has influenced the way we archive, represent, and disseminate information [7]. From papyrus to scrolls, and from Gutenberg’s printing press to typewriters, paper has been a critical medium for augmenting human memory.

Paper has also influenced the way we interact with digital information. Vannevar Bush sought to extend the capabilities of paper by envisioning an electromechanical device, the Memex [12], that rapidly accessed and stored vast amounts of documents stored in microfilms. More recently, when computers sought to radically alter the way we interact with information, scientists at Xerox Palo Alto Research Center (PARC) used paper-based metaphors [47] to make computer interfaces user-friendly. For example, the Xerox Alto and Star displayed electronic documents as black text on white windows mimicking printed paper. Information was managed using concepts such as files, folders, and the desktop, resembling an office workspace. These concepts, collectively known as the desktop metaphor, are central to the present day Graphical User Interface (GUI).

The affordances of digital media were perceived to be superior to the print medium and heralded the concept of the Paperless Office [102], i.e., it was predicted that record-handling would be mostly electronic by the 1990s.

However, paper has proven to be a resilient medium. It continues to be widely used in knowledge work [77]. Sellen & Harper, in their seminal work, The Myth of The Paperless Office
[77], conducted an ethnographic study of knowledge workers to understand the continued popularity of paper. They outlined some of the reasons for this: paper provides tactile-kinesthetic feedback when organizing and navigating information; paper, as a physical medium, is also thin, lightweight and portable; it provides 3D spatial organization of information, while enabling parallel access to multiple streams of information [70].

The tactility and spatial affordances of paper (Figure 1) are key to its continued, albeit decreasing [95], usage. We can rely on haptic cues for handling and retrieving multiple sheets of paper reducing reliance on our visual attention. Paper can also be held at different angles and distances [77,87] to ease reading under different lighting conditions. Computer screens, on the other hand, cannot be manipulated with similar dexterity.

One advantage of organizing physical information on a desk over managing digital windows on a computer desktop is that the location of paper remains perceptually stable, a concept known in psychology as object persistence [68]. Furthermore, the spatial layout is not limited to a single (small) screen, but encompasses all of the knowledge worker's 360º vicinity.
This enables a worker to concurrently access multiple documents and store them with ease. In addition, people organize paper documents in distinct spatial positions on a desk. For instance, in stacks of physical documents, a document’s position corresponds to its age; older documents are lower in the stack [62,63]. Such organizational methods also ease the information retrieval process [70].

These tangible and spatial affordances of paper have been abstracted out or lost in the GUI. For example, it is difficult to represent paper’s rich haptic stimuli visually. There have been attempts to replicate paper’s physical properties of folding [22] and piling [2] on a GUI with little benefit beyond aesthetics. Researchers have also evaluated software window management techniques on large-display tabletop computers that replicate the ease of physical picking, shuffling, and stacking documents [81,87,90]. However, due to limited haptic feedback, bimanual interactions with virtual documents are problematic, as is selecting documents based on their virtual elevation [87].

Figure 2. Flexible displays allow for the physical manipulation of digital information, resembling paper. DisplayStacks [11] (Left) and PaperTab [32] (Right).
With the advent of flexible displays\(^1\) (Figure 2), which begin to approach the weight, thinness and flexibility of paper (Figure 1) with the affordances of digital media. These new display technologies, such as flexible electrophoretic ink and flexible organic light emitting diodes (FOLEDs) [55], will potentially allow users to access and navigate digital information with methods that physically resemble those of paper documents. For example, a ‘sheet’ of paper made with a flexible display could contain an entire book. Such paper can dynamically alter the displayed content based on change in context. Information can be shared and transferred between multiple sheets of paper. In addition, sheets of paper can be moved around, stacked, and spread around the physical environment while continuing to maintain their digital properties.

This thesis presents two new classes of devices: Flexible Computers (a single-display computer that uses a flexible display) and Paper Computers (a multi-display computer that uses flexible displays), where each digital document is fully embodied within an interactive flexible display. These devices support spatial manipulation of digital documents. Design and implementation of a flexible computer (Snaplet) and two paper computer prototypes (DisplayStacks and PaperTab) are discussed. The role of low mass and flexibility in the efficiency of spatial interactions with paper computers is established by conducting Fitts’ law studies.

### 1.1 Motivation

Human evolution has been aided and accelerated by the use of physical objects and tools [5,88]. This has equipped us with cognitive advantages when manipulating the world around us. Research exploring these advantages, within the context of cognition [41] and problem solving

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\(^1\) I refer to Electrophoretic Ink or Flexible Organic Light Emitting Diode (FOLED) displays.
53,94], have triggered a long-standing debate: what is the tradeoff of benefits between physical objects and digital user interface elements for accessing and manipulating digital information?

This has motivated HCI researchers to move beyond the desktop metaphor [47] and explore alternate paradigms of interacting with digital media, i.e., Tangible User Interfaces (TUIs) [43], Organic User Interfaces (OUIs) [39], Reality-based Interaction (RBI) [44], Natural User Interfaces (NUIs) [91], etc. However, TUIs, focusing on using physical objects as handles for digital information, and NUIs, focusing on gesture-based interactions, have largely ignored the physical and spatial affordances of electronic paper.

Paper, as a medium, continues to be used widely in information management [77]. This has led to a vast body of research that has attempted to compare and contrast traditional WIMP interface of computers with paper. Researchers have compared, for instance, the reading [1,70,77], navigation [64], manipulation [87] and organization strategies [62,77] used in digital media with those of paper. This body of work has led to an enduring research goal: the vision of a physical desktop computing system based on the way office workers use paper documents [40,89].

In this thesis, revisiting this research goal, we propose to take the “interface” of paper and apply it to digital media, specifically by enabling information to be embodied in an interactive paper-like form. We envision a class of devices, Paper Computers, in which users can grasp, move, and organize digital documents embodied in multiple flexible displays, within their physical environment. We ground our design of paper computers in the paradigm of Organic User Interfaces, while drawing inspiration from the body of research comparing paper with digital documents.

While there have been various approaches [13,14,40,50,89] to implement paper
computers, the emerging technology of thin-film flexible displays [55] appears most suited for our endeavour. Flexible displays are particularly unique with respect to traditional displays: they are sufficiently thin to approximate paper-like interactions for, e.g., piling documents one on top of one another, and sufficiently light to handle multiple displays at once, as well as manipulate them spatially. While deformability is a feature of flexible displays, their extreme thinness and lightweight are key design elements that make them ideally suitable for physical manipulation. If displays are too thick, stacks become too difficult to hold. When displays are heavy, it becomes difficult for mobile users to carry stacks of displays in their pocket or purse.

Motivated by the opportunities enabled by flexible displays, this thesis tries to answer the following questions:

1. What are the defining features and characteristics of a Paper Computer?
2. How can we support the process of designing interaction techniques for paper computers?
3. How can we take advantage of the physical properties of flexible displays to interact with digital media?
4. Are thin and lightweight displays necessary for paper computers?

1.2 Problem Statement

Thesis Statement

*Flexible low mass displays combine the tactility and malleability of paper with the speed and versatility of digital media. Systems using multiple flexible displays can support newer forms of interaction techniques, for manipulating digital information, that are tactile, spatial, and two-handed.*

---

2 By ‘traditional’, I refer to any rigid, flat, and glass-based computer display.
This thesis addresses the following three sub-problems derived from the thesis statement. A detailed description of the contributions of this thesis is offered at the end of this chapter.

**Sub-problem 1:** To explore the design space for paper computer interfaces, high fidelity prototypes with functional flexible displays are needed.

**Solution:** Develop high fidelity paper computer prototypes that utilize multiple flexible electrophoretic ink displays and thin-film sensors.

**Sub-problem 2:** Existing research in flexible display interactions is confined to interacting with a single, small display. There is very little work exploring multi-display interactions.

**Solution:** Develop interaction techniques for multi-display paper computers that take advantage of the affordances of flexibility, thinness, light weight of flexible displays.

**Sub-problem 3:** It is unclear whether flexibility and low mass of flexible displays are beneficial for spatial interaction techniques.

**Solution:** Elicit user feedback for the proposed interaction techniques. Furthermore, conduct empirical studies based on the Fitts’ Law [10] comparing the efficiency of moving displays of varying flexibility and mass.

**Sub-problem 4:** What defines a Paper Computer?

**Solution:** Reflect on the design of Paper Computers and formalize the definition of Paper Computers.
1.3 Terminologies

We define terminologies that will be used in the rest of this thesis.

**Flexible Display**: Electronic visual display where the pixels and the transistors controlling them are deposited onto a flexible substrate making the entire display flexible. Currently available flexible displays use either electrophoretic ink technology or Organic Light Emitting Diodes (OLED) technology.

**Traditional Display**: Electronic visual display where the pixels and the controlling active matrix are deposited onto a rigid substrate, typically glass. An example is a Liquid Crystal Display (LCD) found in flat panel TVs.

**Flexibility**: Physical property of displays that indicate their ability to be bent. The amount flexibility of a display is measured using **Bend Radius**.

**Bend Radius**: Measure of the smallest radius of the inner curvature of a display surface up to which it can be bent without breakage or creasing.

**Thin-Film**: Single layer or multiple layers of thin and flexible material (0.1 mm to 1.0mm) having sensors or inherent electrical properties.

**Flexible Computer**: A computer with a single flexible and interactive display.

**Paper Computer**: A computer with multiple flexible and interactive displays.

**Electrophoretic Display**: A display technology (also referred to as electrophoretic ink display) invented at Xerox PARC by Nicholas K. Sheridan. It was originally known as the Gyricon rotating-ball display. Each active pixel in an electrophoretic display is made of a spherical microcapsule. Inside this capsule electrically charged white and black pigments are suspended in a clear liquid. They can be moved around in the capsule, electronically, to form text and graphics.
Electrophoretic ink displays require no power to hold the information displayed. They also have high reflectivity and contrast, closely resembling printed paper.

**Fitts’ Law**: A mathematical model, used by HCI researchers, for predicting movement time ($MT$) in GUIs and evaluating different input devices. Movement of input devices (for example, a mouse pointer, stylus, or touch) is modeled for predicting the time taken to acquire a target (for e.g. to predict the time taken to select an icon of width $W$ at a distance $A$ using a given input method).

\[
MT = a + b \log_2 \left( \frac{A}{W} + 1 \right)
\]  

\[
ID = \log_2 \left( \frac{A}{W} + 1 \right)
\]

Equation (1), known as the Shannon formulation [59], is used to predict the $MT$ in seconds. The logarithmic component of this equation is called the Index of Difficulty ($ID$), measured in bits. Input device performance is calculated and reported as a single statistic—the Index of Performance ($IP$)—in bits per second ($bps$). $IP$, also referred to as throughput, encapsulates both speed and accuracy of the measured input device. There are multiple methods of calculating the $IP$ using $MT$ and $ID$. We discuss them in section 2.5.1. In this thesis, we use the terms Index of Performance and Throughput interchangeably.

**Mass vs. Weight**: While mass is a fundamental measure of the amount of matter in an object (measured in Kilograms), weight is measure of the force experienced by an object due to gravity (measured in Newtons). However, within the context of this thesis, mass and weight will be used interchangeably, i.e., devices of low mass can be described as being lightweight.
Units of Measure: All measurements in this thesis are reported in the metric system. However, display dimensions, following display manufacturer norms, are reported in inches indicating the length of the diagonal of a display.

1.4 Contributions

This thesis presents interactive paper computer prototypes that are enabled by functional flexible displays. We demonstrate techniques for interacting with digital information that take advantage of asymmetric bimanual input [33] and spatiality in display interaction. Furthermore, we also provide empirical evidence to assert that flexible displays offer key advantages over traditional displays for spatial interactions.

Specifically, we answer the previously outlined three questions and state that:

Contribution 1: We used flexible displays to build high-fidelity, multi-display, paper computer prototypes for deployment and evaluation of paper-like interactions. We report on the design and implementation of three flexible display prototypes: Snaplet [84], DisplayStacks [29], and PaperTab [86].

Snaplet is a wearable device (using a 3.7” flexible electrophoretic ink display) that adapts its function based on its shape and position in relation to the user’s body. DisplayStacks is a multi-display paper computer that explores stacking as a metaphor for interacting with data, in a mobile form factor (using 3.7” flexible electrophoretic ink displays). PaperTab is a paper computer comprising of multiple, large (10.7”) context-aware flexible electrophoretic ink displays supporting spatial and proximity based interactions. The displays are tracked in 3D enabling users to bimanually interact with multiple streams of information similar to handling sheets of paper.
DisplayStacks and PaperTab were inspired by DigitalDesk [89] and PaperWindows [40], systems that placed the GUI in the real world and onto a user’s desk. The distinction in this research is that the displays are real, made with flexible electrophoretic ink technology. This allows for developing, for example, a device that incorporates display and sensing in a wearable form factor (Snaplet), not affected by issues of occlusion or limited viewing angle common to projected displays.

Due to the current limitations of battery and chip technology, flexible displays in my paper computer prototypes are tethered to their rigid driver electronics with long flexible flat cables, essentially offloading the computation from the displays. This limits the portability of the prototypes.

**Contribution 2:** *We designed spatial and bimanual interaction techniques taking advantage of the affordances of flexible displays.* The thinness and low mass of flexible displays enables us to develop interfaces that access multiple digital documents bimanually, spatially and concurrently. The flexibility of these displays, i.e., the ability to bend or shape them without breaking, can provide rich tactile-kinesthetic (haptic) feedback when handling them and also support bending the display [55] as a form of input. With Snaplet, we explore how flexibility provides an interaction context for a wearable device that fits the body.

With DisplayStacks, we take advantage of the thinness of displays to explore stacking as an interaction metaphor. With PaperTab, we combine these affordances with the low mass of displays to present a physical computing interface that enables 3D spatial organization of information, as well as parallel access to multiple data streams. We introduce two categories of interaction techniques for PaperTab: *Between-display* and *Within-display* interactions.
Between-display interactions encompass spatial and proximity-based interactions with displays on a desk. For example, collocating multiple displays together or panning a display across a desk. Within-display interactions introduce the concept of selecting and interacting with information within a display by using the tip of another display. We present the results of a qualitative study to show how the presented interaction techniques can be easy to learn, without inducing significant physical demands or mental demands.

**Contribution 3:** We evaluated different display types and demonstrated that electronic paper computing environments benefit from the use of flexible displays. Aside from Fitts’ original experiment [23] there is little empirical evidence whether low mass and flexibility are indeed beneficial for spatial interactions. Fitts’ Law [23] is a highly successful mathematical model used by HCI researchers to compare the performance of different input methods in GUIs and novel interfaces. Previous work into Fitts’ Law studies of flexible display interactions [20] has focused on pointing efficiency on the surface of a flexible display. The study has shown that flexibility can be a detriment in terms of pointing efficiency. However, the performance benefits of using a flexible and low mass display for spatially interacting with information has not been established.

It could be argued that in multi-display physical windowing environments, where users move many physical displays around on a desk, flexible and low mass displays are desirable. We demonstrate this with Fitts’ law experiments, by comparing how devices of varying mass and rigidity perform in Between-display and Within-display interactions.

We set the following hypotheses for our three Fitts’ law experiments:

**Hypothesis 1 (H1).** Displays with a lower mass will have a higher index of performance
(see section 2.5.1 for a definition of this term), when moving them on a desk, than displays with a higher mass. This aligns with Fitts’ observations in his seminal experiment [23].

**Hypothesis 2 (H2).** Flexible displays will have a higher index of performance, when moving them on a desk, than rigid displays.

**Hypothesis 3 (H3).** Index of performance will be higher with displays that are Flexible (H3.1), and with displays of a lower Mass (H3.2) when displays are used for pointing tasks within displays.

**Hypothesis 4 (H4).** Index of performance will be higher with displays that are Flexible (H4.2), and with displays of a lower Mass (H4.2) when displays are used for dragging tasks within displays.

**Minor Contributions:** We formally define the term *paper computer* (a multi-display computer that uses flexible displays) to identify its contribution and role within the larger paradigm of OUIs. During our prototype building efforts, we explore various ways to implement networked multi-display interfaces. We reflect on the challenges and benefits of different software and hardware architectures for enabling networked multi-display interfaces.

**1.5 Thesis Outline**

Chapter 2 discusses the related work. We begin with a summary of the takeaways from *The Myth of the Paperless Office*. Furthermore, we look at the need for bridging the physical world and the different frameworks that have attempted this. Works exploring, specifically, the confluence of paper and digital media for interactions will be presented. We survey the landscape of interaction techniques for digital media that focus on spatial manipulation as well as multi-display
interactions. We conclude our literature review by presenting evaluation strategies used by many of the previously presented research work.

Chapter 3 presents the design and implementation of Snaplet, a wearable flexible computer. Based on the experience of building Snaplet, the implications for designing multi-display paper computers are discussed.

Chapter 4 discusses the design, implementation, and interaction techniques for DisplayStacks, a handheld multi-display paper computer. Interaction techniques that use piling as a metaphor for interacting with digital information are presented. A novel method for sensing piling of multiple thin-film displays is introduced. This chapter concludes with an evaluation of the DisplayStacks sensing hardware.

Chapter 5 discusses, in-depth, the design and implementation of different versions of a full-size paper computer, PaperTab. Interaction techniques for spatial manipulation of digital information with PaperTab prototype will be presented. We conclude the chapter with a qualitative evaluation summarizing users’ experience of interacting with PaperTab.

Chapter 6 presents quantitative evaluation of paper computers. Three Fitts’ law studies are presented that explore Between-display and Within-display interactions with devices of varying rigidity and mass. Results are presented and discussed. Reflecting on our prototypes and the Fitts’ law results, we formalize the definition of paper computers.

Chapter 7 concludes this thesis by outlining our contributions, limitations, and future work.
Chapter 2

Literature Review

This chapter is in part based on [29,84,86]

2.1 The Myth of the Paperless Office

Sellen and Harper, in their seminal work, The Myth of the Paperless Office [77], investigated the way office workers used paper for information creation, transfer, storage and retrieval. They were motivated to understand the continued popularity and increasing usage of paper documents despite the availability of electronic computers in offices and optimistic predictions heralding the paperless office [102].

Based on their observations and interviews, they describe some characteristics of printed paper that may explain its continued popularity. Rigid graphical user interfaces often use an input device—typically the mouse—that is indirect, one-handed, and dependent on visual cues. By contrast, paper documents:

1. Are thin, low-weight, allowing superior portability.

2. Have many physical pages, each page pertaining only to a specific and physically delineated task context.

3. Provide variable screen real estate that fits the current context of use.

4. Use physical bend gestures with strong tactile and kinesthetic feedback for efficient navigation.

5. Allow documents to be laid out, or collocated for easy access.
However, compared to digital media, paper has its limitations:

(1) It is static and changing or updating of information on paper is not straightforward.

(2) An increase in the amount of information we need to access leads to a linear increase in the number of sheets of paper we need to use.

(3) It not easy to search or sort information quickly.

These limitations draw attention to the unique affordances of digital media. Janet Murray [69] lists the following affordances of digital media: it comprises of executable instructions - it is procedural; digital information and the underlying procedures can be manipulated - it is participatory; it has the ability to encompass vast sets of information - encyclopedic; it can be navigated structurally and across virtual spaces.

It is clear that there is scope for building interfaces that merge the advantages of interacting with paper to those of digital media. Sellen and Harper [77] provide the following guidelines for designing paper-inspired digital interfaces. They suggest that any new electronic document interface can be improved by supporting:

(1) Flexible navigation by providing richer haptic feedback, direct input methods, and more extensive bimanual input.

(2) Cross-document use by allowing collocation and stacking of multiple documents. In addition to collocation, they also suggest providing simple methods for document comparison, and cut/copy/paste operations.

(3) Annotations while reading.

(4) Interweaving reading and writing.
(5) Generic devices that support cross-referencing, collaboration, and form-filling activities.

Sellen and Harper’s observations of the use of paper as well as the above design guidelines formed a key motivator in driving our design choices for paper computer interfaces.

2.2 Bridging Physical and Digital Worlds

The way we interact with objects in our physical world is largely different from the way we interact with the digital world of computer interfaces. We use our fine and gross motor skills to manipulate multiple physical objects simultaneously, with both of our hands (bimanually) [33]. In addition, the way we use physical objects has provided us with certain cognitive advantages [94]. This has motivated researchers to bridge the physical world of atoms with the digital world of bits and bytes.

In his Kinematic Chain theory, Guiard observed that in bimanual interactions, the hands coordinate behavior in an asymmetrical manner [33]. He noted that we rely on our non-dominant hand to provide a frame of reference, responsible for coarse movements and positions, while our dominant hand performs fine-grained work, relative to the motion of the non-dominant hand. These highly developed fine and gross motor skills, and rich tactile-kinesthetic feedback, are underutilized when we interact with traditional computer interfaces.

In exploring differences between basic organization tasks in physical and digital media, Terrenghi et al. [87] noted that digital media lacked the ability to be manipulated in 3D, or to provide multimodal tactile feedback, an important quality of physical media such as paper documents [77]. They observed a predominance of one-handed interactions in digital tasks, while bimanual interactions were predominant in the physical tasks.
The theory of distributed cognition [41] describes how we use physical objects around us for reducing our cognitive efforts in problem solving. For example, it is easier and faster to solve a Tower of Hanoi puzzle [94] by physically moving the discs rather than by performing mental computations while looking at them. Based on this, Fitzmaurice showed, with Graspable User Interfaces [25,26], that physical objects required lower effort and attention for manipulation than GUI elements. He further showed that specialized graspable objects performed better in data manipulation tasks than generic objects. Tangible User Interfaces (TUIs) [43] expanded on these observation and presented a class of interfaces and associated interaction techniques where users interact with digital information through physical handles. Siftables [67] is an example of a TUI where users can grab, stack, throw, bump together interactive physical blocks with LCD screen on them. The blocks can sense one another and react to the users’ actions and, based on the context of operation they display the outcome on the screens.

Motivated by the advances in thin-film and flexible electronics, Organic User Interfaces (OUIs) [39] extended the paradigm of TUIs by envisioning a tight coupling of physical objects of any shape with digital interfaces by attaching high-resolution flexible displays and thin-film electronics onto non-flat geometries. OUIs presented design guidelines for developing interfaces and interactions beyond flat displays.

OUIs are defined by three core design principles [39]:

**Input equals output:** There is a tight coupling of the input and output in an OUI—*the input device is the output device*. This is in stark contrast to the direct manipulation interface [42] of keyboard and mouse or the ‘physical handles’ of TUIs [43], acting as proxy for digital information represented elsewhere.

**Function equals form:** The form of a device determines its intended function.
*Form follows flow*: An OUI, building upon the previous principle, can change its shape to suit the context of use.

Interfaces developed with flexible displays fall into the category of Organic User Interfaces: non-flat, flexible, tactile, high-resolution display interfaces. OUIs take advantage of flexible displays to develop devices that can fall under one of the three categories: rigid but non-flat; deformable by the user; self-actuated. Our proposed Paper Computers, using flexible displays, fall into the category of deformable Organic User Interfaces.

### 2.3 Paper-like Manipulation of Digital Media

The idea of exploring tangible, paper-like interactions with digital media, specifically by embodying electronic information onto interactive paper-like medium, is far from new.

Wellner's DigitalDesk [89] was one of the first paper computers. Wellner envisioned that, rather than use metaphors of a physical desk to develop computer interfaces (as was the case in developing the GUI), it would be beneficial to bring a computer interface onto the physical medium of paper. He developed DigitalDesk to seamlessly merge interactions between physical paper and digital documents on a physical desk.

With DigitalDesk, users were able to select data from paper documents and copy it into digital documents. This was achieved by projecting interactive elements onto a sheet of paper placed on a desk. A camera captured users’ input as well as tracked printed paper on desk, while computer vision algorithms detected hand pose and selection actions, and performed character recognition of printed data that was selected. DigitalDesk showed some example scenarios, for example, users could directly select numbers printed on a report and enter them into a calculator projected on a blank sheet of paper.

In PaperWindows, Holman et al. [40] created a windowing environment that simulated
fully wireless, full color digital paper. The position, orientation and deformation of physical sheets of paper were tracked in 3D using motion capture cameras. This was used to project and tightly couple active computer windows directly onto the blank sheets of paper for interaction purposes. PaperWindows demonstrated use of gestural inputs such as hold, collate, flip and bend.

All of the above systems use projection for displaying digital information onto paper. However, projection based systems have certain limitations. They are affected by problems of occlusion. Users can only interact with projected surfaces within the projection boundaries. Such systems are also bulky as they depend on projectors and large 3D tracking systems to enable interactions.

Tabletop Computers or surface computers are another approach to providing paper-like interactions with digital information. Khalilbeigi et al. [50] and Steimle et al. [81] worked on a tabletop system that tracked various configurations of physical documents. They explored the concurrent interactions with physical & digital documents on an interactive surface. Hinckley et al. [37] combined pen and touch interactions to support bimanual note-taking and scrapbooking on an interactive tabletop system. While tabletop systems benefit from a large interaction surface and multi-touch gestures, they are still restricted to the two-dimensional surface, with limited haptic cues.

Chen et al. [14,15] presented the design and development of a fully functional multi-device system for supporting active reading tasks, based on paper interaction methods. Each device featured a custom-built rigid e-book reader (weighing 500g) that could operate independently or coupled with one or more devices for cross-referencing, duplicating, and copy-paste operations. They described interaction techniques for reading, navigation, and annotation tasks with documents.
This approach of using interconnected multiple tablet devices overcomes the issues of projection-based (i.e. not portable) and tabletop (i.e. limited to 2D) systems. Further research is warranted to understand how rigidity and mass might affect the users’ performance, when interacting with such devices.

2.3.1 Interaction between multiple displays

The paper computer systems presented above, with the exception of tabletop systems, all include multiple devices for supporting concurrent access to multiple documents. It is therefore beneficial to explore simpler ways of interacting and transferring information between multiple devices. Bumping displays together [34,67], and pouring data from one display to another [40,67] have been used in commercial mobile devices and custom multi-device interfaces for coarse-grained operations such as copying contents or establishing connections.

In the Pick-and-Drop [72] technique, users can pick and drop objects between multiple displays using a stylus as a (virtual) container of digital information being transferred. Chen et al. [14,15] designed the Conduit technique for bimanual transfer of information between two devices. In their system, the non-dominant hand chooses the target device while the dominant hand selects the specific item for completing the action (select/transfer/copy).

Several systems and interaction techniques have used devices as peripheral to (larger) tabletop surfaces. Interactions between such devices take on the role of a focus+context interface [8], i.e., a large display provides the information to be navigated, while one or more smaller devices help determine the focus of interaction. PaperLens [79] is one such system where a standard Letter-sized display is used to spatially navigate data being presented underneath it on an interactive table. For example, a user holds a display in their hand and moves around the 3D cross-section of a human body in all six degrees of freedom. Here, the larger displays, underneath
the user’s hand and to the side, show the context for navigation. PhoneTouch [75] introduces using the tip of a mobile phone to touch an interactive surface for initiating actions. PhoneTouch supports simultaneous interactions with multiple mobile devices as well as users’ hands.

2.3.2 Flexible Displays

The emerging technology of thin-film flexible displays [55] presents an opportunity to merge the physical world of paper with the digital world of information. Flexible displays are sufficiently thin to approximate paper-like interactions, and sufficiently light to allow for efficient spatial interactions between displays. The availability of functional flexible displays necessitates further research to develop paper computer prototypes where a digital document is fully embodied in a single flexible display. We can take advantage of the paper-like qualities of such flexible displays to further adopt metaphors of paper-based interactions for digital data manipulation.

Manufacturing of flexible displays has been primarily fueled by a pragmatic need for decreasing the size and weight of existing smartphone and tablet devices as well as increasing the robustness of these popular interaction devices [96]. While this is beneficial for our research, we have to note that the available displays were not necessarily designed with flexibility as a feature. This poses some challenges of prototyping with such displays, as we will discuss in future chapters.

Research in thin-film display interactions started with paper mockups, bendable substrates on rigid devices [76] and projected flexible displays [40]. Gummi [76] was a bendable prototype with a rigid LCD on the front and a flexible substrate attached to its back. Discrete and continuous bending of the flexible substrate was explored as novel way of navigating information. With the recent availability of working flexible displays, projects like PaperPhone [55], FlexView [11], and FlexCam [19] explored bending as an interaction paradigm. PaperPhone
featured a smartphone-sized display augmented with bend sensors. With a participatory user study, it identified users’ preferred bend gestures for simple data navigation tasks on a flexible display. PaperPhone can be termed as the first fully functional flexible computer prototype.

2.4 Spatial Manipulation of Digital Information

Researchers have focused on designing interfaces that replicate some of the spatial organization methods of paper on digital interfaces. Specifically, there has been considerable work in exploring stacking and collocation as metaphors for organizing and manipulating digital information.

2.4.1 Stacking

Stacking physical documents is one of the main forms of spatio-temporal organization of information. On physical desktops, piling\(^3\) is an advantageous method of organizing documents as it can be done on any flat surface. Compared to filing, piling is a lightweight, casual activity that requires little overhead [62]. Piling allows elements to be easily repositioned within a pile and reorganized between piles [90]. Moreover, piles are most useful in tasks using visual features of documents [45].

**Digital Piles**

Mander et al. [63] introduced the pile metaphor to browse and manipulate sets of digital documents. Their 3D piles were presented either with a disheveled appearance to indicate user-created piles, or with a neat look, indicating system-created piles. Beaudouin-Lafon [9] created physically-inspired digital piles through Rotated Windows, displaying a top-view pile of “loose” documents. The user peeled back the top window to reveal the lower window. In BumpTop,

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\(^3\) In our work, we make a distinction between Stacks and Piles (see Chapter 4.) However, existing literature appears to use the two terms interchangeably.
Agarawala and Balakrishnan [2] presented pen-based interaction and visualization techniques to manipulate groups of electronic documents on a computer desktop using physically-simulated piles. Key elements of their prototype included the ability to create, toss, and drag documents, create neat and messy piles, and to support pile browsing with a variety of widgets. Our work aims at creating a physical instantiation of these digital piles.

With tabletop computing, Davidson and Han [17] extended the physical metaphor of layering interactions to move between overlaid windows. Users could push the side of a virtual document to lift the other side, and move it atop. Aliakseyeu et al. [4] investigated interaction techniques for browsing tabletop piles, by allowing piles to be partially, or entirely opened up to reveal their content. Results show that fast techniques are not always preferred, concluding that engagement and effort should be used to evaluate piling techniques, as performance is not always a sufficient measure.

Hybrid Piles

Hybrid piles combine the advantages of physical manipulation with the power of digital information. Existing research investigates two types of hybrid piles: (1) piles of paper documents, tracked on a digital tabletop or by a video camera, or (2) electronic documents on a pile of portable devices. Khalilbeigi et al. [50] presented interaction techniques for paper piles on tabletop, a good example of the first type of hybrid piles. Their flexible reorganization scheme laid out fluid transitions between neat piles and full juxtaposition, by displaying the documents linearly in a vertical or horizontal matter, or by fanning them out.

While we find additional related work in the first hybrid category [40,45,76,77], the second type of hybrid document is of interest for paper computers. PaperWindows [40] is an early example of these hybrid piles, created through projection on blank sheets of paper. In developing
an interaction language for electronic paper documents, Holman et al. collated documents to stack them in piles. Until now, current technology has not been conducive to the creation of these hybrid piles because of the thickness of displays available. One can hardly imagine stacking tablets to store or access digital documents. With flexible display technology, we identify an opportunity to explore electronic documents as a pile of displays.

2.4.2 Collocated Displays

Recent work on spatial arrangements of documents and displays has focused on the physical colocation of displays. For instance, Chen et al. [13] explored the use of dual display e-book readers, in back-to-back or side-by-side configuration. To turn a page, users flipped the back-to-back display device, while, on the side-by-side display device, they brought the right display towards the left one. Dual displays were found to have the potential to improve the reading experience.

In addition to placing each document on a different display and arranging them spatially [40], researchers have explored increasing screen real estate by joining multiple collocated computers. This technique is often used to present a single document on two or more screens [34,97] or to extend the desktop to both [34,36,67]. It can also display additional information about a document, such as a broader overview [13].

To solve the interaction problem faced by dual collocated displays, Hinckley et al. explored connecting two computers through Synchronous gestures [34], and created gestures spanning two displays [36].

2.4.3 Tracking Documents

Various systems have been developed to track relative and absolute positions of physical groups
of objects and documents. Previous works on tracking piles of paper and books have used radio-frequency identification (RFID) tags [6], computer vision [28,52], motion capture systems [40] and conductive inks [65].

Back et al. [6] used thin RFID transponders embedded in each page of a book to track the currently opened page. While this system tracked the changes in a stack of pages, it did not detect the ordering nor the change in page order.

Kim et al. [52] used a video camera to record the changes in the state of documents on a desk and process the video frames to construct the position and relative structure of the documents. However, this system could not track the documents in real-time, nor could it track the occluded documents. Fujii et al. [28] made use of a video camera and half-mirror to track the objects in a stack based on the height of the objects. While this method enables interactions such as thumbing through the stack, it does not work for paper or other thin objects.

While these systems explore interesting approaches to tracking of objects, they either require specialized desk setups, including cameras [28,40,52], or they limit the tracking to a fixed order of documents [6,65].

To detect collocated displays in ConnecTable, Tandler et al. [83] used passive tags based on radio frequency transponder technology. When two computers are moved close, ConnecTable creates a shared space by combining the personal spaces. Siftables [67] explored the use of several small square displays to create playful interactions. The displays detected their own motion with accelerometers, and their close proximity to each other through IrDA infrared transceivers. Other methods of detecting collocated devices include bumping displays [34], detected through accelerometers, or using ultrasound transducers to automatically determine the relative location of devices [54], through measures of distance and angular bearing between
devices. Hoffman and Scott [38] developed ‘Networked Surfaces’ where location and orientation of multiple devices were determined by the use of electrical contact sensing on physical surfaces.

It is interesting to note that generic high-precision 3D tracking systems (such as motion capture systems [40]) can enable the tracking of displays that are piled as well as collocated. They can also support 3D spatial interactions that go beyond collocation.

2.5 Evaluating Flexible Display Interactions

Lee et al. [57] evaluated gestures with different deformable materials: paper, cloth, and plastic. This was an exploratory study to understand gestures for future flexible devices. Users were asked to create gestures for 11 different tasks using the three given materials. Surprisingly, high flexibility elastic cloth was found to be most preferred and having the lowest planning time. They also observed prevalent use of bimanual input [33]. BendFlip [92] empirically evaluated page navigation techniques on flexible and rigid form factors. They identified that bending, as an input, can be as efficient as the press of a button for flipping pages in electronic book readers. Dijkstra et al. [20] evaluated the efficiency of pointing and dragging on the surface of a flexible device. They showed how structural holds create temporary rigid zones in these flexible devices, allowing for more efficient pointing operations in these zones. Although these evaluations focus on deformation as input, they do point towards the feasibility of using flexible displays in lieu of tablet devices for most of the interactions.

Comparative evaluation of novel interfaces, both qualitatively and quantitatively, is challenging [67]. This is primarily due to two factors: interaction techniques of existing systems and novel systems may support different affordances that makes it impossible to have a meaningful comparison; also, results may be biased towards more established systems due to familiarity and robustness. For this reason, our qualitative evaluation of paper computers does not
include comparisons with GUIs or other interfaces.

However, Fitts’ law [23] has been used extensively for comparing the efficiency of different interaction approaches in target acquisition tasks. We conduct three Fitts’ law tasks to evaluate devices of varying flexibility and mass to understand the importance of these two properties in spatial manipulation tasks, such as moving displays on a desk.

2.5.1 Fitts’ Law

Fitts’ Law [23] is a mathematical model that is used by HCI researchers for predicting movement time in GUIs and for evaluating different input devices [32,48,60,61]. Typically, in Fitts’ law studies, movement of input devices (for example, a pointer, stylus, or touch) is tracked for reciprocally acquiring two targets in the interaction space (Figure 3). Targets vary in width ($W$) and in the distance between two targets (i.e. amplitude $A$), leading to unique task conditions. Multiple iterations of each task condition (for target acquisition) is performed for each of the different input devices or methods. Movement time, error rate, and other relevant parameters are recorded. This data is used to build a mathematical model that predicts the movement time of any given input method.

\[
MT = a + b \log_2 \left( \frac{A}{W} + 1 \right) \tag{1}
\]

\[
ID = \log_2 \left( \frac{A}{W} + 1 \right) \tag{2}
\]

In equation (1), known as Shannon’s formulation [59], $MT$ is the movement time between two targets at distance or amplitude $A$ and of width $W$. The logarithmic component (Eq. (2)) is called the Index of Difficulty ($ID$). Parameters $a$ and $b$ in Eq.(1) are obtained through a linear regression of movement times obtained from tapping with a pointing device between two targets.
of varying amplitude and width. Input device performance is calculated and reported as a single statistic—the Index of Performance (IP)—in bits per second (bps). IP, also referred to as throughput, encapsulates both speed and accuracy of the measured input device.

Existing Fitts’ Law evaluations have used two different approaches to calculating IP. Most studies compute the IP as the reciprocal of the empirically determined constant $b$ in Eq. (1).

$$IP = \frac{1}{b}$$

Soukoreff and MacKenzie [78] recommend using mean-of-means (see Eq. (3)) to compute the IP for task conditions, especially when comparing different devices or task conditions. Here, $IP_{e,i}$ is the effective Index of Difficulty computed using Eq. (2), where $A$ and $W$ are replaced with $A_e$ and $W_e$, i.e., amplitude and width values adjusted for accuracy for each of the $xA-W$ pairs and $y$ participants (see [78] for a detailed explanation of this correction).
2.5.2 Area Cursors

With the “Prince” Technique, Kabbash and Buxton [48] introduced area cursors for selecting point targets. They showed how Fitts’ Law applied to this scenario when \( W \) was computed as the width of the cursor instead of the target width, with a very good fit.

Area cursors are square or rectangular in most designs. Modeling such cursors for 1D analysis of typical 2D tasks requires additional corrections to the model [60] that account for the actual width based on the approach angle. The Bubble cursor [32] was implemented with a circular area cursor that alleviated this problem and showed a very good fit for the Fitts’ law equation.

2.5.3 Fitts’ Law Evaluation of Tangibles

While numerous Fitts’ law based studies exist for GUIs, few studies have explored evaluation of tangibles using Fitts’ Law [16]. The seminal paper of Fitts [23], identifying the relationship between information capacity and tolerance of a movement task, included experiments involving tangibles. Fitts compared styli of different weights in a reciprocal tapping task (Figure 3). His two other experiments involved transferring plastic discs of different sized holes (Figure 4, left) and
pins of different weights (Figure 4, right), respectively. In recent studies, Rohs et al. [74] used a two-component Fitts’ law model to predict target acquisition in a mobile augmented reality scenario. Christou et al. [16] proposed a model to predict reaching-to-grasp movements based on the associated amplitude. While these are sound models for evaluating their proposed tasks, we believe that the Fitts’ law model, along with a derivation of the “Prince” Technique [48], would be useful for evaluating the basic premise behind the use of flexible thin-film displays in multi-display environment: that they are easier to move around on a desk and better suited for pointing than traditional display devices. This is because movement of the display, rather than a cursor within the display, is best modeled by considering the display as an area cursor.

2.6 Summary

In this chapter, we surveyed prior work that motivated our research questions as well as guided our design choices for building flexible and paper computer interfaces. We summarized the takeaways from The Myth of the Paperless Office that forms the cornerstone of our research. We then discussed the need for bridging the physical world and the different frameworks that have attempted this. Works exploring the confluence of paper and digital media for interactions were discussed. We surveyed the landscape of interaction techniques for digital media that focus on spatial manipulation as well as multi-display interactions, both key to the design of paper computers. We concluded our literature review by presenting evaluation strategies used by prior research work for estimating pointing performance. In the next chapter, we present our first flexible display prototype, Snaplet, laying the foundation for exploring the design space of flexible computers.
Chapter 3

Snaplet: A wearable flexible computer

This chapter is in part based on [84]

Figure 5. Snaplet, a wearable flexible computer. It switches its application context to watch and media player when worn in a convex shape.

In this chapter, we describe the design and implementation of Snaplet, a wearable flexible computer, in the form of a bracelet. With Snaplet, we explore the design space of mobile flexible computers. We discuss lessons learnt from designing and building Snaplet and how these will guide us in developing multi-display paper computers.
Snaplet is a wearable flexible electrophoretic ink display augmented with sensors that allows the shape of the display to be detected. When in a convex shape on the wrist, Snaplet functions as a watch and media player. When held flat in the hand it is a PDA with notepad functionality. When held in a concave shape Snaplet functions as a phone. Returning it to a flat or convex shape drops calls. Snaplet marks our first effort into developing a fully interactive shape changing flexible computer.

3.1 Introduction

Mobile devices are electronic chameleons, changing from phones to notebooks to maps to media players at a click. They are no longer static single function tools, but are instead powerful general-purpose computers with increasingly sophisticated sensors and communication systems connecting them to the world.

As is typical with multi-function tools, sacrifices in individual application performance are traded for versatility. Moreover, the ergonomic relationship of the phone to the user’s body is diminished in quality by the requirement to have a flat display. The screen real estate is less than ideal for viewing media because the device must fit in the user’s pocket.

Interaction modalities with mobile devices have evolved with their functionality. When mobile phones were only phones, interactions were limited in duration and complexity and conformed to the familiar rules of their wired progenitors. With new functions came new buttons, GUIs, touch screens, and a whole range of other sensors. Interactions are now much more prolonged and diverse in nature.
We propose that future mobile computing devices are developed with flexible displays. This will address many problems plaguing current hardware. These flexible devices will be lightweight and will not have the rigid bodies and glass screens that can break when dropped. They can conform to shape of the user’s body, enhancing the ergonomic relationship, yet be flat when that form is called for. Their flexible nature facilitates comfortable and fashionable wearable designs with flexible screen real estate. While the concept of bendable computers has been discussed before [40,57,76], the implementation of such a computer has been delayed by

Figure 6. Snaplet, when held flat, changes to a PDA with pen-based note taking functionality.
technical difficulties [57]. With the availability of functional flexible displays, specifically, the Arizona State University Flexible Display Center (ASU FDC) 3.7” ‘Bloodhound’ flexible electrophoretic display [71], we created the first functional flexible computer.

We present Snaplet, a first example in this new category of flexible display devices. This mobile computer can be worn on the wrist, allowing hands-free viewing or one handed interactions, or can be snapped off and held in the hand during phone calls or for (bimanual) focus tasks. Snaplet takes advantage of the affordances provided by the flexibility of the device to produce a new interaction paradigm: the shape of the user’s body determines the shape of the device, and accordingly, its current function. Our Snaplet prototype demonstrates how the way the user holds a flexible device can lead to the alteration of its physical form, which in turn can alter its functionality.

Snaplet uses bend sensors to classify the shape of the device. This information drives a state machine, which determines which applications to run and what commands to perform based on the calculated context of use. Snaplet uses pressure sensors to detect screen touch. Finally, Snaplet uses a Wacom flexible tablet to allow stylus interaction.

3.2 Snaplet
Snaplet was designed for three wearable application contexts: a watch context (Figure 5), a PDA context (Figure 6) and a mobile phone context. Each context is associated with a limited number of mobile application functions. To use Snaplet as a watch, a user places the flexible screen along the curvature of their wrist, horizontally, bending it downwards. The user affixes the curved display on the non-dominant arm, on a shirt or a removable sleeve using Velcro. In this context, the user can watch a video, or play with a music application using touch interactions. To use it as a PDA, the user removes the device from the wrist, and holds it flat inside the palm of the (non-
dominant) hand. Users can use their dominant hand to interact with the display using a stylus, or using deformation of the display. In this context, the user can read a book, take notes or sketch on the display. Users can pick up a phone call by bending the edge of the display with their fingers, then placing the device to their ear.

3.3 Design Rationale

The goal of our design process was to develop interaction techniques for wearable flexible computers by taking advantage of the flexibility of thin-film displays. We identify functionalities that are beneficial for such devices:

3.3.1 Function Equals Form

The ability of flexible displays to deform renders them capable of conforming to non-planar surfaces. Within the scope of wearable devices, a flexible display can change shape based on where it is in relation to the user’s body. Following the principles of Organic User Interfaces [39] we should ensure that the function of the display adapts to such change in form in meaningful ways.

3.3.2 Dynamic Bends

Bending a part of a flexible display temporarily [55] has been used in prior research to trigger actions [55] or as navigational aids [92] in interactive systems. We note that such gestures can be supported, in addition to other forms of input, to trigger different functions in a flexible device.

3.3.3 Multimodal Interactions

It is necessary for a wearable flexible device to support different levels of input (coarse versus fine, discrete versus continuous) to enhance mobile interactions. Our challenge lies in identifying possible input methods that we can support on a device having a thin and deformable surface.
3.4 Flexible Interaction Techniques

We propose two dimensions of deformations that guide flexible interaction techniques. First, we classify gestures using their immediacy, where we find static and dynamic actions. Second, we classify according to the deformation of the display, afforded by the body part where the screen currently is located (e.g. wrist, palm). We also implemented pen and touch input to further enrich the interaction experience of Snaplet.

3.4.1 Static Bends Provide Context

The most basic input in Snaplet is the static bend shape. The shape (or, rather, bend) of the display surface along the vertical (portrait) axis determines the wearable application context of the device. A convex shape allows Snaplet to function as a watch, a flat shape allows it to be used...
as a pen-based PDA, and a concave shape takes the phone off-hook. These shapes conform to the shape of the body in various wearable contexts: respectively, wrist, flat hand and grasping hand, thus producing distinct functional affordances [57].

Static bends offer visual and tangible cues of the current wearable context and application mode of the device, allowing the user to make high-level menu or application selection. For instance, holding the phone in a concave shape requires a force, which provides haptic feedback that signifies an ongoing call. Releasing the haptic energy directly corresponds to dropping the call.

3.4.2 Bend Gestures Trigger Actions
Our second category of actions consists of active bend gestures, which provide functions within a wearable application context. Bend gestures allow the user to interact with specific applications, or change applications in a given context. These actions are mostly metaphorical rather than designed around the body shape, and the action produces an immediate, visible result, such as pulling down a menu, scrolling or paging forward. To avoid cross-talk with the static bends, bend gestures in this category are limited to deforming corners on one side of the display (Figure 7).

Bend gestures are used in the PDA context, as they are impractical in both wrist and phone contexts. Given the current physical constraints of the display, there are only a few possible bend gestures: bending the top right corner, upwards or downwards, and bending the bottom right corner, upwards or downwards [55]. A combination of those four corner-bends is also possible, for instance by lifting both corners up.

3.4.3 Pen/Touch Interaction
To enrich the interaction styles of Snaplet, the user can use touch interaction (through pressure sensors) as well as with the stylus. Pen interaction allows coordinate pointing and richer input
such as sketching or taking notes (Figure 6). Touch interaction is the input source for icon navigation and menu selection.

In all, Snaplet offers varied input: bend, pen and touch. The simultaneous combination of inputs may also produce a wealthier interaction language by providing contextualized actions. For instance, in the context of note taking, the combination of bend and pen at once could allow access to select/cut/copy/paste actions. The user could bend the top corner upwards to start selecting text, releasing the corner to stop selection. The user could use the bottom corner to indicate whether to cut or copy, respectively by bending the corner up or down. Finally, the user could paste the text at the location indicated by the pen by bending the top corner downwards.

3.5 Implementation

We set the following goals while building the prototype. We wanted to interface with the flexible display hardware, i.e., the AM 300 driver board, and deploy interactive applications. In addition, we wanted to attach sensors to the flexible display device while maintaining the device's low mass and flexibility. Lastly, the prototype should provide insights into the strengths and limitations of the current generation of flexible display hardware and how it may impact interactivity.
The PaperPhone [55] prototype (designed and developed in our research lab) was the first to incorporate a fully functional flexible display for bend interactions. We mirrored many of the PaperPhone’s hardware and software features and extended them when designing the Snaplet prototype.

Snaplet consists of an Arizona State University Flexible Display Center 3.7” ‘Bloodhound’ flexible electrophoretic display (Figure 8.b), augmented with a layer of five Flexpoint 2” bi-directional bend sensors, six pressure sensors, and Wacom digitizer. The
prototype is driven by an E Ink [98] Broadsheet AM300 Kit (Figure 8.a) featuring an embedded Linux processor.

An Arduino Mega microcontroller (Figure 8.c) obtains data from the Flexpoint bend sensors and pressure sensors. Pen tracking functionality, i.e., a Wacom digitizer, directly interfaces with the AM300 processor. The AM300 and Arduino are connected to a laptop running a Max patch [99] that processes sensor data, performs gesture recognition and sends images to the display.

### 3.5.1 Bloodhound Flexible Display

The flexible display (Figure 8.b) used in Snaplet was provided by ASU’s Flexible Display Center. The dimensions and other technical details of the display are listed in Table 1.

At 0.6 mm thick and 10 g weight, the Bloodhound display is ideal for wearable scenarios. The display uses the electrophoretic ink technology that requires no power to hold the images displayed making it ideal for low-power devices. The reflective properties of electrophoretic ink are also ideal for use in different light conditions.

However, the display’s bend radius is only 60 mm. This implies that the display cannot be bent at very sharp angles during interactions. In addition, the display has sensitive electrical

<table>
<thead>
<tr>
<th>Display Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Display Area Dimensions</td>
<td>76.8×57.6 mm (i.e. 3.7” diagonal)</td>
</tr>
<tr>
<td>Outer Display Dimensions</td>
<td>96.80×81.90 mm (i.e. 5” diagonal)</td>
</tr>
<tr>
<td>Resolution</td>
<td>QVGA (320×240 px)</td>
</tr>
<tr>
<td>Weight</td>
<td>10 g</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Bend Radius</td>
<td>60 mm</td>
</tr>
</tbody>
</table>
connections on one side that power the pixels. This hardware design limits the amount of the display that can be bent and prevents bending along the axis parallel to the short side of the display.

The display resolution, size, and pixel density are fairly low in comparison to LCD displays found in contemporary mobile devices. In addition, it cannot be used in low-light conditions due to the lack of backlight. Lastly, the FDC’s displays are meant for prototyping purposes and cannot be used for extended periods of time.

Despite the limitations of the display, we will be demonstrating how its functions are sufficient for designing high-fidelity flexible display prototypes.

### 3.5.2 AM300 Display Driver Kit

Each Bloodhound display is controlled and driven by a custom E Ink kit, i.e., the AM300 Display Driver Kit (Figure 8.a). This kit includes a Gumstix single board computer with Linux operating system. This kit has a built-in support for reading inputs from a flexible (Wacom) digitizer pad, allowing for precise pen inputs. The processor can interface with a computer via a USB interface. The kit also has its own battery supporting limited portability.

An Epson display driver controls the flexible display and allows drawing up to 16 levels of gray with two different refresh rates. Updating the entire screen takes 780 ms, i.e., the screen refreshes at approximately 1 frame per second ($fps$). Parts of the display can be updated to white or black in 260 ms, i.e., at 3 $fps$. These faster updates are ideal for the notepad application which requires only black pixels to be drawn. The slower screen updates are used for other interactions. The kit includes simple drawing routines for pixel-addressed drawing and to draw pre-rendered images on screen.
3.5.3 Sensing Interactions

We use an array of 5 bend sensors for tracking the deformations of the flexible display. To ease the design of the sensor layout and to ease the mounting of the sensors on the back of a flexible display, we designed and built a flexible printed circuit (FPC). We built the FPC by printing its design on DuPont Pyralux flexible circuit material with a Xerox Phasor solid ink printer, then etched the result to obtain a fully functional flexible circuit substrate. A step-by-step method of how our FPCs are designed and built is presented in Appendix A. We then mounted (i.e. soldered) the bend sensors onto the FPC and subsequently on the back of the display itself.

To support precise input on a display, we use a flexible Wacom digitizer with a pen. To support coarse input on the display, we use an array of 6 pressure sensors. This allows simple
touch operations within different application contexts. Figure 9 shows the different sensor layers mounted beneath the flexible display.

3.5.4 Software Implementation

Snaplet application control software is written in Max. This application is deployed on a personal computer (PC) which interfaces with the AM300 and Arduino. Max is a visual programming environment that simplifies interfacing with multitude of sensors and visualizing the data flow. Both AM300 and Arduino communicate with the Max patch via a serial connection over USB.

The user interface screens are pre-rendered as images and loaded onto AM300 board. The sensor input from the Arduino is processed by the Max patch and instructions are sent to AM300 board to display the appropriate UI onto the Bloodhound display.

Wearable application contexts are distinguished automatically by the system through recognizing the shape of the display. Snaplet uses a k-Nearest-Neighbor (kNN) algorithm with k=1 to recognize bend gestures. kNN assigns the label of the most similar examples (the closest neighbor) to the example to classify. In our case, the examples are vectors from the live values of the 5 bend sensors. This recognition algorithm requires only a single training input for each gesture, making it ideal for rapid programming of user defined bend gestures. A bend gesture is recognized when the display is bent to a curvature that is closer to a recorded shape than a flat shape.

3.6 Discussion

We believe the Snaplet prototype is the first functional example of a flexible electrophoretic ink display that incorporates bend, pen and touch input for application context sensing. Snaplet demonstrates how the form of such devices can naturally follow that of the body throughout different interactions. Not only does this improve ergonomic aspects of the device, providing a
comfortable fit to the hands and wrist, it also provides direct affordances that associate shape with the function of the device.

A third advantage of this particular use of a flexible display is its haptic qualities: forces exerted when performing bend gestures, whether static or dynamical, inform the body of the current functionality of the device. This means that, similar to stick shifts in cars, users can utilize the shape of the device for eye-free context switching, relying on haptic rather than visual feedback to determine the current state of the device [58].

We should note that due to the state of technology, the current design of Snaplet has some, hopefully temporary, drawbacks. We designed Snaplet as a wireless display. However, the display and sensors require a cable bundle that interferes with a comfortable one-handed grasp of the display. Also, the fragile display connectors require one side of the display to remain rigid, thus limiting the flexibility of Snaplet. In addition, gesture designers must be aware that holding patterns and static device shapes restrict the number of available dynamical gestures. An investigation of how people hold mobile devices, such as PDAs, may further aid in designing around these issues. When designing deformation-based gestures, attention seeking movements and physically uncomfortable gestures should be avoided, as they may influence the adaption of the technology [73].

For ergonomic fit, Snaplet should follow the body’s shape. However, in some cases, there is more than one body shape the device could follow. For instance, when in a phone call, the device could mold to the curvature of hand or the face. We selected to follow the curvature of the hand as the user needs a comfortable grip to talk.

With Snaplet, we were able to successfully interface with the flexible display driver and various sensors to control the user interface based on user input. The low refresh rate of
electrophoretic ink displays could limit the range of interactive applications that can be deployed. However, it was sufficient to demonstrate the feasibility of different interaction techniques.

The prototype was less than portable owing to the external display driver and the use of a PC as the primary processor. This is the nature of currently available flexible display technologies and limits our ability to conduct long-term user studies with Snaplet.

Using the PC as the host device for managing interactions speeded up the design iterations since loading programs and images onto the AM300 board was relatively slow. It must be noted that faster development cycles and more efficiency could be achieved by moving away from Max to other high-level programming languages (e.g., C++, C#, Java).

### 3.7 Summary

In this chapter, we discussed Snaplet, a wrist-mounted flexible electrophoretic ink display augmented with sensors that sense the shape of the display. Interaction techniques presented in Snaplet follow the principles of OUI design. Snaplet can thus be categorized as an OUI. When in a convex shape on the wrist, Snaplet functions as a watch and media player. When held flat in the hand it is a PDA with notepad functionality. When held in a concave shape Snaplet functions as a phone.

Implementing the Snaplet prototype provided us with insights into the strengths and limitations of the current generation of flexible display hardware and how it may impact interactivity when building multi-display paper computers.
Chapter 4

DisplayStacks: Interaction Techniques for Stacks of Flexible Thin-Film Displays

This chapter is in part based on [29]

In this chapter we present the design, implementation, and system evaluation of DisplayStacks, a mobile paper computer comprising of multiple flexible displays. DisplayStacks allows us to explore the design space of interacting with multiple mobile displays simultaneously by relying on the affordances of thinness and low mass of flexible displays.

Stacking physical documents is one of the main forms of spatio-temporal organization of information. We present DisplayStacks, a system that enables physical stacking of digital documents via piles of flexible electrophoretic ink displays. With a conductive dot pattern sensor attached to the flexible display, we dynamically track the position and orientation of these displays in relation to one another. We introduce mechanisms for interacting with these physical stacks for access and manipulation of information using asymmetric bimanual interactions, such as providing contextual overviews. Initial user experiences indicate a strong preference for linear overlaps as a stacking configuration.

4.1 Introduction

Considerable effort has been put towards the development of computers that use multiple physical displays to represent windows into a digital content [13,14,50,89]. Wellner [89] early-on outlined some compelling reasons for this: 1) interaction techniques for digital documents are limited, and distinct from those used with paper; 2) the physicality of paper provides users with
richer forms of interaction that are deeply embedded in their tactile-kinesthetic systems 3) paper allows for efficient switching between multiple, parallel, documents; and 4) the reflective properties of paper provides for a superior reading experience.

In the real world, paper documents are often stored in ways that provide distinct spatial correlates. For example, in stacks of physical documents, the lower the document, the older it is
One advantage to the organization of information in physical stacks over the organization of digital windows on a computer desktop is that the location of windows remains perceptually stable. Furthermore, the spatial layout is not limited to a single small screen, but envelopes the user, easing retrieval of documents pertinent to foreground or background tasks. While research in surface computing has explored software window stacking and hybrid physical-digital stacking techniques that replicate the ease of physical picking, shuffling, and stacking for document access and manipulation [81,87,90], bimanual interactions with virtual stacks of documents are problematic, as is selecting documents based on their virtual elevation [87].

Thin-film flexible displays, with their unique physical properties of thinness and low mass, allow us to reconsider physical organizational metaphors of paper in organizing digital documents. While we find prior research on physically grouping digital documents according to location (i.e. collocation) [34], there has been little to no work on physically stacking digital documents: current display technologies are simply too thick to be stacked in meaningful ways. While flexibility is a feature of these, we believe their extreme thinness and low mass are the key design elements that make flexible displays ideally suitable for stacked designs. If displays are too thick, stacks become too difficult to hold. When displays are heavy, it becomes difficult for mobile users to carry stacks of displays in their pocket or purse.

Sellen and Harper [77] point out that physical stacks and piles are often used in offices to organize and navigate documents on the fly. We believe the use of stacks of thin-film, physical electrophoretic ink displays may have several clear advantages over virtual windows for the organization of documents: 1) Physical piles support crude ordering of related information while maintaining parallel access to multiple documents; 2) Stacked physical windows are not hidden
and remain visible and tangible in the z dimension; and 3) Physical windows are more easily handled in groups, e.g., to serve as context-aware tool lenses into other windows in the stack.

4.1.1 Contribution

In this chapter, we propose DisplayStacks, a system for physically organizing digital documents via stacks of thin-film electrophoretic ink displays. Our main contributions are: 1) the introduction of an electronic paper computer, i.e., a computer that uses multiple thin-film electronic paper displays, in which each computer window is represented by its own paper-like display and 2) techniques for interacting with stacks of such displays. While work exists on stacking digital displays, the low mass, thinness and flexibility of these displays allow for novel interactions that mimic paper document navigation. As these interactions require thin-film sensing technologies, we propose a method for dynamically tracking the position and orientation of these displays relative to each other using a conductive dot pattern sensor layer affixed to the bottom of each flexible display. We also collected tracking accuracy and user experiences in an initial user study.

4.2 Displaystacks

DisplayStacks (Figure 10) represents a first step towards a generic paper computer interface: one that relies on interactions with flexible displays, one in which each computer document is represented by its own flexible display. It closely resembles DigitalDesk [89] and PaperWindows [40], systems that sought to bring the virtual desktop to the real world, with the distinction that our displays are real, made with Arizona State University (ASU) Flexible Display Center’s (FDC) 3.7” ‘Bloodhound’ thin-film electrophoretic displays [71]. While ideally our prototype would have used sheets of 8.5”×11”, displays of this size were not currently technically feasible.
Displays are augmented with thin-film bend, location and orientation sensors that allow the displays to be aware of their stack location and occlusion by other displays.

### 4.3 Basic Stacked Interaction Techniques

In DisplayStacks, we explore stacking interaction techniques with multiple displays facing the same direction. Here, we discuss input and interaction techniques through physical configurations created when grouping overlapping displays (Figure 11). We built on traditional configurations
and input techniques in the literature, and expanded both the basic sets (in this section), and the set of complex interaction techniques (in a later section).

4.3.1 Pile
A pile is a loose grouping of partially overlapping displays (Figure 11.a). A loose set of displays can allow the user to rearrange documents, such as shuffling cards, or pictures. Users can interact with documents in a pile by moving the displays among the arrangement, and inserting them throughout. This would be the typical way to access and reorder a document in an analog pile.

4.3.2 Stack
A stack is a neat, organized arrangement of displays (Figure 11.b). The user can insert displays at different locations within the stack, or bend the displays to flick through them.

4.3.3 Fan
A fan configuration is formed by a set of displays shaped in a partial circle pattern (Figure 11.c). It is similar to how players hold a set of cards in their hands. In addition to insertion, the user can rotate, or fan, a display along the fan’s pivot, formed typically by the stack’s bottom corner. The fan as a display was explored briefly by Lee et al. [56], and fanned piles by Khalilbeigi et al. [50].

4.3.4 Linear Overlap
Displays can be arranged in a linear pattern, with partial overlap (Figure 11.d). Steimle et al. [81] refer to this representation as Spread-out. The user can cover or uncover the displays to interact with them by sliding the displays along the linear configuration, as well as insert them as necessary. The uncover interaction technique increases the visible part of the bottom display.
4.3.5 Collocation
Displays can also be side-by-side, collocated [34,35,40], when sharing one edge (Figure 11.e). The user can interact with the displays by collocating them.

4.3.6 Transitions and Combinations
It is interesting to note that the user can move through the physical configurations by covering and uncovering displays. Starting in stack mode, the user moves to the horizontal linear overlap by uncovering the top display, and ends up with collocated displays. Khalilbeigi et al. [50] identified these fluid transitions in hybrid paper-and-electronic documents on tabletops. We expand it for stacks of electronic documents on flexible displays.

Physical configurations can be combined to create more meaningful interactions with stacked displays. While the illustrations in Figure 11 only make use of two displays, we imagine most interactions with stacked displays will use a minimum of three or four displays [52].

4.4 Design Rationale
The goal of our design process was to develop tools for organizing digital documents using physical piles and stacks. We identify a number of functionalities typically associated with stacking physical documents that serve as metaphors for the development of complex interaction techniques and applications that ease the following:

4.4.1 Contextual Overview
Partial stacking can make it easier to get an overview of multiple documents at a time. This is particularly apparent in games of cards, where fanning behaviors allows a user to hold multiple documents, while the content of each display remains identifiable.
4.4.2 Organizing and Sorting

Stacks and piles can contain documents organized according to some parameter, for example time. By stacking incoming documents on a desk, workers can use relative location in the stack to retrieve documents by date. However, traditional piles can be hard to sort. We aim to merge the ability to determine order through relative location in the pile with the ability to sort documents automatically.

4.4.3 Layering Information

In cell-based animation, stacks of translucent sheets make it easier to work with layered information. By physically shifting documents between layers, information can be moved relative to that of other documents. We use the layer ordering idea, and borrow from translucent sheets by digitally showing information from displays below.

4.4.4 Nonlinear Browsing

Stacking can ease casual browsing through documents. An extreme example of this is a book, a perfectly neat stack. However, even when documents are not stapled together, being able to insert the finger into a pile and pull up a location in the document allows for physical random access based on location in the pile.

4.4.5 Partial Viewing

The flexibility of paper documents allows for partial bending of individual documents and partial stacks as a means for browsing the content of the pile without necessarily shifting the order of, or moving individual documents.
4.4.6 Real Estate Increase

In magazines, centerfolds or fold-out spreads allow an increase of the real estate available.
Instead of being restricted to images that fit on a single document, the image can be split and
displayed on multiple pieces of paper.

4.4.7 Contextual Information

The content of paper documents can support that of other documents. Magazine inserts provide
additional information, or half page covers display the headlines, while the full-page cover
contains the name of the magazine and the photography of a personality.

4.5 Design Constraints

We followed a number of design principles related to the actual physical relationship between
display and user:

4.5.1 Bending as an Input Metaphor

While flexibility of the display was not a primary concern, we were inspired by some of the
bending techniques used in physical document stacks to access information on hidden sheets, and
used these as metaphors throughout our design process. Firstly, when browsing a paper stack
linearly, users often bend the top corner of a paper sheet to reveal or partially reveal information
on the sheet below it. Secondly, when browsing non-linearly through a book, users often bend
multiple sheets of paper, for example, to go to a next chapter or index. Thirdly, we were inspired
by the use of bends to sort decks of cards, and of dog-earing multiple pages together as a means
of binding sorted stacks, and used it as a metaphor for sorting stacked sheets. Finally, we used the
metaphor of lifting a transparency sheet from a stack as a metaphor for adjusting transparency in
layered documents. Although touch interactions were not technically feasible, our prototype does include stylus interactions.

4.5.2 Two-handed use

We designed our interaction techniques such that they follow patterns of two-handed interactions observed in using paper documents. Not only can bimanual interactions be more efficient, two hands are often required when handling multiple documents [33,37]: one to hold the stack, the other to handle individual documents in the stack. Specifically, the non-dominant, generally left hand typically holds the stacks, while the dominant hand interacts with individual displays, e.g. through a stylus, a behavior consistent with Guiard’s kinematic chain theory [33].

4.5.3 Thinness and Low Mass

The main features of flexible displays that make them suitable for stacking, however, is not their flexibility, but rather, their thinness and low mass. Stacks of thick displays are difficult to hold with one hand, like a stack of cards. We designed our system such that it would potentially be easy to carry the stacks in a pocket. This meant the displays needed to not just be thin, but also as lightweight as possible. Finally, we believe weight plays a role in the dexterity with which individual displays can be moved within and between stacks.

4.5.4 Input

One of our interests lies in stacking displays as a mean of providing input. To leverage the flexible nature of the displays, we explore bending as a mean of triggering sorting behaviors in piles and stacks of displays. Our displays are further augmented with stylus input, e.g. to select items on the screen.
4.5.5 Type of Display

We believed it important to use displays that resemble the reflective properties of paper. While flexible electrophoretic ink display has the disadvantage of having a relatively slow refresh rate of over 260 ms, it resembles physical paper documents more than any other available display technology. Given limited availability, quality and life expectancy of FOLEDs, we chose to work with available 3.7” ‘Bloodhound’ flexible electrophoretic ink displays [71] that we used, earlier, in our Snaplet prototype.

4.5.6 Screen Size and Ergonomics

Being unable to explore full size interactions with 8.5”×11” sheets, we focused on designing mobile interactions with the 3.7” display making sure to allow easy holding of a stack with one hand. Unlike Snaplet, we chose to fold all the display circuitry underneath the display to limit the bezel, allowing a stack of at least three displays to be easily held with one hand. The compound displays measure 5” (12.68 cm) diagonally with bezel. Note that the flexibility of thin-film displays enhances the ergonomics by allowing a better fit of stacks to the palm of the hand.

4.6 Using Displays as Tools

Our basic set of interaction techniques can be combined to form more complex interactions informed by our design rationale. We use displays both for content, but also as contextual tools to manipulate content located on other displays. These include:

4.6.1 Contextual Overviews

To take advantage of the partial screen available in fanned displays, our system allows the user to see a contextual overview of each document in the stack, located on the visible screen portion. Contextual overviews give enough information to identify the content of the document without
viewing it in its entirety, exploiting the visual features of the document [45]. In a game of cards, when a hand is fanned, the player sees a “summary” of each card—a colored letter or number, and an image of the suit. Hence, to improve the identification of each display, we digitally augment this action by showing a contextual overview of each document, such as a thumbnail, or a variable from that document, such as the title, date, or version. When working with a spreadsheet, fanned displays give the user an overview of the whole document, with each tab on a different display (Figure 12).

4.6.2 Contextual Menus

Fan: One of the problems users face working with single display devices is that valuable screen real estate is often occupied by tool palettes and menus. Contextual menus allow one display to contain contextual tools that can be applied to a second screen. For example, in a painting application, the top display may hold the canvas, while the bottom display holds a palette of paint
tools, and the middle display a menu of brush icons. Fanning the displays allows users to increase and decrease the number of tools available. As each display detects what part of the screen real estate is covered, different tools and brushes are displayed in the exposed space, according to frequency of use. A user can dip his or her Wacom stylus onto the second display to select a tool or brush that can then be applied to the top display to draw.

**Linear Overlap:** Similarly, contextual menus can be popped up across displays by uncovering a display in the stack to a linear overlap position. This serves as a focus + context feature in which the focus may remain on the top document, while a secondary display serves to provide context surrounding that document. For example, when reading a book on the first display, the second display can pop out to the left to show a thumbnail overview of the chapters or pages in the document (Figure 13). Pages can be selected from the menu using a stylus, after which the front
display shows the selected content. We apply contextual menus proposed by Chen et al. [13] and Khalilbeigi et al. [49] to linear overlap.

4.6.3 Linear Browsing of Piled Information

Piles are stacks that are not neatly organized. In piles, both the location and orientation of displays may be different from display to display (Figure 11.a). When users view information on piled displays, not only may information on a display lower in the stack be partially covered by a higher display, they may also need to reorient displays prior to being able to view the information correctly.

Our system allows users to browse information located on lower displays on the top display, in a linear fashion. Bending the top corner of the top display towards the user causes content to cycle through the pile of displays (Figure 14). This interaction technique is inspired by how people go through piles of documents to find the relevant one [70], as well as by Rotated
Windows [9]. In a three-display pile, upon a bend, information on the middle display is loaded onto the top display, information from the bottom display is loaded onto the middle display, and information on the top display is moved to the bottom display. This allows for a linear browsing action common to piles of unsorted information, like photographs, such that the graphics are always displayed on the top display in the proper orientation. Piles may be held with the non-dominant hand or placed on a surface.

4.6.4 Non-Linear Browsing & Sorting of Stacked Information

One of the problems with stacks is that they can be tedious to sort [51]. Our system handles sorting automatically by transferring information between displays according to some variable, such as date and time of creation, or alphabetically. A bend of the top right corner of the entire stack away from the user sorts the information on the displays according to the first variable, a second bend according to the second variable, and so forth.

For instance, a set of displays that represent electronic business cards picked up at a conference may be placed in a pile, then arranged in a stack. Bending the set of displays away from the user causes the business cards to be sorted by last name. Bending it again causes them to be sorted by date and time at which the card was received. Bending it again sorts the cards according to nationality, while a final bend renders them unsorted again. Business cards can be browsed linearly, i.e., in order of display, by bending the top right corner of the top display towards the user.

A second problem of stacks is that displays obscure each other. In the physical world, documents need to be pulled out in order to be viewed. Our system allows bends of multiple displays towards the user to actuate non-linear browsing. Linear browsing is actuated by bending the top right corner of the top display towards the user. For example, if each display contains a
chapter of a book, bending the first display will page through the first chapter. With non-linear browsing, the user bends multiple screens, e.g., the first, second and third display simultaneously, which places the third chapter onto the top screen. This bend swaps the two chapters: the first chapter is now displayed on the third screen. Single bends of the top screen now allow paging through the third chapter. A second bend of the first, second and third display causes the chapters to return to their original order.

4.6.5 Merging and Splitting Documents

Documents that span multiple displays in the stack can be merged into a single document on the top display by bending the left side away from the user. The bottom displays become blank after the merge operation. Individual pages in a document displayed on the top display can be split into separate documents on the other (blank) displays in the stack by bending the left side of the stack towards the user.

4.6.6 Layering and Transparency

With physical stacks, the use of transparencies (e.g., overhead projector slides) allows for see-through effects that have proved useful in cell-based animation, photography, architecture and medicine. Stacks of thin-film displays offer two main advantages: to control 1) the digital transparency level of images, and 2) the position and orientation of layers to create aligned graphics. By using physical stacks, every layer is physically represented, and can be pulled out of the stack in order to be examined in isolation, or to be reordered.

While in the stack, the level of transparency of individual layers (i.e., displays) can be adjusted by bending its bottom right corner of the corresponding display in the stack, with an upwards bend increasing the level of transparency. The transparency level of groups of displays
can be altered by bending the bottom right corner of the set of displays. Alternatively, users can use a fanned display menu that provides contextual menus that control transparency. To create a specific composition, the user can apply linear and non-linear browsing as well as sorting techniques to the layers through bends of the top right corner of the displays. Once an appropriate layering of information has been achieved, layers can be flattened (merged) by bending the left side away from the user, leaving the user with a single display that shows the composite outcome.

4.6.7 Increasing Screen Real Estate through Collocation

One way of solving the problem of limited screen real estate is to collocate two separate displays such that they form one single, larger screen [34,36]. Linear overlaps can be used in this process to continuously widen a display to the exact size needed. Once the displays are collocated, applications adjust automatically to the larger canvas. While browsing a map on a stack of three displays, the area shown on the map can be enlarged to three times its size by uncovering one display to the left, and another to the right of the central display. Another example is in an increased sketching canvas space. Note that our system currently has the disadvantage of introducing visible bezels that obscure part of the display.

4.6.8 Physical Sorting and Insertion

The stack of digital displays retains all the benefits of being able to physically sort the displays by popping them in or out of the stack. Physical tying of information to a particular display, however, is overridden with any of the interaction techniques that move information between displays. This means there is no strong tie between information and any one particular display.
4.7 Implementation

To implement the interaction techniques described, we augmented a number of flexible electrophoretic ink displays with stack sensing technology. The DisplayStacks prototype tracks the relative position of the flexible display screens in a physical stack as well as the dynamic movement/repositioning of the displays within the stack. Based on the interactions by the user, the displays are updated to reflect changing states of location and orientation in the stack. Within a pile, our display regions change dynamically to present context-specific content. To our knowledge, no prior work exists that has demonstrated these techniques with flexible thin-film displays.

We created the system using 3 displays, but DisplayStacks is scalable to as many flexible displays as are needed for a particular application. We believe a plurality, i.e., 3 displays, suffice to explain most techniques, such as bending the corner of a single display for non-linear browsing, or of the entire stack for sorting, which all scale up. Kim et al. [52] noted that stacks can be as small as 3 or 4 displays. The primary goal of building DisplayStacks prototype was to realize a functioning multi-display paper computer and its associated stacking interaction techniques in a thin-film form factor. We followed an iterative design approach.

4.7.1 Conceptual Design and First Prototype

The core challenge for our prototype was to sense display-stacking in a thin-film form factor. We outlined multiple potential designs and focused on our simplest idea: completing an electrical circuit when two displays stack one on top of another.
We designed two flexible circuits: one that contained a $4 \times 4$ grid of protruding conductive dots beneath a display; another circuit contained 4 conductive zones above and around a display.

Figure 15. Rough prototype (first iteration) consisting of conductive zones (left) and $4 \times 4$ grid of conductive dots (right) mounted on foam and cardboard.

Figure 16. Final prototype. Detecting relative location of displays using an asymmetric pattern of conductive dots. Front of display (left) and back of display (right).

We designed two flexible circuits: one that contained a $4 \times 4$ grid of protruding conductive dots beneath a display; another circuit contained 4 conductive zones above and around a display (fully
taking advantage of the wide bezels around the display). Stacking two displays would form connection between the conductive dots and the zones. Each dot had a unique signature that would allow us to track not only the stacking of displays but also their orientations and approximate positions when stacked.

We built our first prototype using foam and cardboard (Figure 15) to validate our hardware design. We identified multiple challenges with our circuit design. First, the conductive dots were not uniformly connected with the underlying display surface. This was due to the variations in the way the flexible prototypes were held. In addition, the density of conductive zones was too low, causing many false positives.

To alleviate these problems, we designed an asymmetric pattern for conductive dots and zones that would be sufficient to demonstrate a subset of all possible display configurations. This approach would allow us to keep the underlying electronics simple. In the next section, we discuss the implementation of DisplayStacks prototype with this asymmetric pattern in detail.

4.7.2 Final Prototype
To implement our interaction techniques, our DisplayStacks prototype uses the same flexible displays as was used in Snaplet, i.e., ASU FDC’s 3.7” thin-film electrophoretic displays [71]. Figure 16 shows a flexible display augmented with thin-film bend and location detection sensors. The total thickness of a display, with the attached sensing layers, is 3 mm. DisplayStacks is currently wired to rigid electronics driving the flexible displays. The displays are given mobility through long ribbon cables.
Each flexible display is augmented with four layers of sensors (Figure 17). The first layer is located along the bottom and left bezel of the display, where the non-dominant hand typically holds the stack, ensuring better connectivity between layers. It consists of seven flexible conductive zones that detect the order in which displays are stacked, laid out on a flexible printed circuit (FPC). The second layer, beneath the display, is a flexible Wacom digitizer. The third

Figure 17. Each display is augmented with 4 layers: a conductive bezel on an FPC, 4 bend sensors on an FPC, a Wacom digitizer, and a conductive dot pattern on an FPC.

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layer has four Flexpoint\textsuperscript{5} 2” bi-directional bend sensors, on an FPC. The fourth layer consists of an asymmetrical conductive dot pattern, with 14 conductive dots, on an FPC. As shown in Figure 16 (right), the dot pattern faces outwards on the back of the display. The dot pattern interacts with the top bezel to determine location and orientation of the displays within a stack. Each dot is 1 \textit{mm} thick, protruding from the display to ensure a properly conductive connection with the bezel of the display below. The two FPCs were built by printing our circuit design onto a sheet of Dupont Pyralux copper coated polyamide using a solid wax printer. To produce the circuitry, the Pyralux was etched using hydrochloric acid, after which the wax was dissolved to expose the circuitry (see Appendix A).

4.7.2.1 Processing

Each flexible display and Wacom digitizer are driven by an E Ink Broadsheet AM300 Kit featuring an embedded Linux processor. An Arduino Mega microcontroller obtains data from the other three sensor layers. The AM300 kits and the microcontrollers interface with a PC over USB interface. An application written in Processing\textsuperscript{6} (also known as a Processing Sketch) processes the sensor data from the Arduino microcontrollers, runs the logic to determine the current state of each display, and updates the flexible displays via the AM300s.

4.7.3 Recognizing Interaction Techniques

Interaction techniques are implemented by interpreting data from the four sensor layers. When two displays are stacked, the conductive dot patterns on the back of the first display connect with the corresponding conductive bezel of the display below. The relative location and orientation of

\textsuperscript{5} Flexpoint Sensor Systems. http://www.flexpoint.com/
\textsuperscript{6} Processing is a simplified version of the Java programming language, designed for electronic arts and visual design communities. https://processing.org/
Figure 18. A subset of the conductive dots of the top display forms a circuit with a subset of the conductive bezel of the bottom display (both sets illustrated in red.) A fanned occlusion is detected in this example.

the displays is based on which dots connect to the bezel. The bend sensor layer enables interaction with the stack using a rich set of bend gestures. A Wacom digitizer allows pen-based interactions with individual displays in the stack.

4.7.3.1 Sensing Location and Orientation

When one display (display-A) is stacked on top of another display (display-B), a subset of the conductive dot pattern beneath display-A makes contact with a subset of the conductive bezel on the front of display-B to form a circuit (see Figure 18). When a conductive dot connects with a conductive zone, this is registered by the Arduino and sent to the Processing sketch. It keeps track of the activated dot-bezel circuits, thus reconstructing the relative position and orientation of
display-A with regards to display-B. When a third display is added below display-B, its relative position and orientation can be determined as well. Stack order is determined by sensing a unique electrical signal sent by each display over its bezels.

4.7.3.2 Detecting Occlusions

When a display is moved in a stack, the system uses its location and position data to compute the size of the area of display-B that is not occluded by display-A. Depending on the state of the display stack, this information is then used to update the graphics on the display. We selected a specific dot pattern (Figure 18) to support stacking, discrete steps of linear overlap along the horizontal and vertical axes and fanning out. Due to the limited resolution of the dot patterns, each display currently detects eight zones of occlusion: 3 partial vertical occlusions, 2 partial horizontal occlusions, and 3 fanned occlusions.

The dot pattern is divided in three zones to recognize the three types of occlusion. Dots along the vertical axis, on the side of the display, recognize vertical occlusions when they come in contact with the left, vertical bezel. Dots along the horizontal axis, on the bottom of the display, recognize horizontal occlusions when they come in contact with the bottom, horizontal bezel. Fanned occlusions are recognized when the dots in the middle of the screen make contact with the bottom bezel (as illustrated in Figure 18). Stacking is detected when vertical dots come in contact with the left bezel simultaneously with horizontal dots coming in contact with the bottom bezel.
The system is robust enough to track 8 different configurations, by maintaining a state machine for each display (Figure 19). The displays start in the unstacked state. In this state, displays can either not be overlapping, or loosely piled. Once aligned, they become a stack. In
this state, the user can thumb through the displays, or insert displays in the stack. The user can also fan out the displays to move to a fan state, uncover the displays horizontally to move to the linear overlap (horizontal) state, or uncover vertically to move to the linear overlap (vertical) state. In each linear overlap state, the user can cover and uncover the displays. Once completely uncovered, the state becomes collocation. Specifically, collocation is currently detected by the change from linear overlap to no contact state. In every state, the user can align the displays to return to the stack, or loosen the displays to return to the unstacked state. While we use redundant dots (e.g. 2 dots can identify the fanned state in Figure 18) and state-tracking to improve reliability and reduce false positives, our simplified sensing increases the possibility of false positives between collocation and unstacked, something investigated in our initial user study.

4.7.3.3 Detecting Bends
We used 4 bi-directional bend sensors, located at the top and bottom right corners, as shown in Figure 17. Users can perform 6 bends with the two pairs of bend sensors embedded in the prototype: top right corner up/down; bottom right corner up/down, and right center up/down. Perpendicular pairs of sensors are used to obtain an optimal measure of the flexion of each corner using redundancy.

4.7.4 Initial User Experiences
We did not pursue a formal user study as the displays being used had a high failure rate when handled for prolonged interactions. However, our sensor design had potential for many false positives. Therefore, we decided to evaluate the accuracy of the sensing technology used in DisplayStacks.

We probed 6 users (2 females, 4 males; 24-28 years; mean=26.17 years). We asked the users to achieve each of the 8 configurations (3 partial vertical overlaps, 2 partial horizontal
overlaps, and 3 fanned overlaps) from the stacked state (repeated 5 times) with two displays. Users were notified of a successful configuration with a message on the top display. Errors were indicated with an auditory beep.

Preliminary results indicated that the system correctly recognized states with varying levels of accuracy for each state. Users preferred the vertical overlap overall which the system correctly recognized with 82% accuracy. Horizontal overlap was less easy to achieve with 77% accuracy. Fanning was not a preferred technique, as it involved more effort than the other techniques (66% accuracy). However, two users learned to pivot the displays by holding the stack with their thumbs, allowing them to execute fanning with the same effectiveness as the other techniques.

Our observations indicated that the tracking was irregular when users held the displays loosely. This pointed out the primary challenge of our current tracking method. Different approaches to tracking the displays, without compromising on the thinness or flexibility of DisplayStacks, would alleviate these issues.

4.8 Discussion

With DisplayStacks, we proposed a set of interaction techniques for electronic documents on thin-film flexible electrophoretic ink displays that enable the physical manipulation of electronic documents in ways similar to paper documents. We believe there are several key benefits to this:

4.8.1 Physicality of Stackable Windowed Content

One of the chief benefits of flexible displays is that they can be integrated into a very thin form factor. This allows user manipulations that are currently not available with LCD-based computing devices. One clear benefit of the use of many thin-film displays in a single workspace is that windowing no longer serves as the primary means of managing workflow between multiple
documents views. Instead, each display correlates with a window. Because the displays are thin, windows can be stacked similarly to electronic windows. We argue that this stacking behavior brings organizational benefits that are difficult to implement using multiple LCD-based displays, if only because their thickness makes it difficult to handle stacks and fans of multiple displays.

4.8.2 Tactile Representation of Windowed Documents

DisplayStacks’ interaction techniques provide tactile feedback in ways that traditional displays do not. Holding stacked displays gives the user tactile information about the total number of displays or windowed documents available. Bending as an input technique allows for a physical correlate that represents the action directly in the muscle receptors of the user [3]. This can help users achieve light-weight interactions without requiring visual attention. Bending multiple screens allows for actions such as sorting to be applied easily across arbitrary groups of (obscured) display devices, as well as be tangibly represented.

4.8.3 Dynamic Display Regions

Within a pile, our display regions change dynamically to present context-specific content. To our knowledge, no prior work exists that has demonstrated these techniques with flexible thin-film displays or with GUI windows. Previous work has discussed collocation with rigid, thick LCD displays [34,36], as well as introduced bookmarks when working with dual electrophoretic ink screens [13]. We believe that the thickness of the stacked displays to be stacked represents a critical design parameter. With DisplayStacks, we expanded the work and presented a number of new configurations (e.g. fan), input techniques (e.g. rotating displays, bending single display, bending piles), and interaction techniques (e.g. contextual overviews, menus, layering, merging documents). These new interaction techniques all make use of either dynamic display regions, or take advantage of the thinness and flexibility of the displays. Note that dynamic updates of
display contents may, however, lead to confusion amongst users during the re-orientation or re-positioning of a display.

4.8.4 Permanence of Information

As we compare the interaction techniques on thin-film displays to those of paper, it is critical to discuss the permanence of information. The information displayed on paper is highly permanent, while the content of a specific display is not. The fixity of content with respect to its medium can help in ad hoc sorting tasks [62], aiding recall for where information is located on a desk, stack or page [51]. As such, dynamic updates of display contents may lead to confusion amongst users when the orientation or position of the display is altered. Note that an important benefit of electrophoretic ink displays is that they hold their contents even when they are not powered. This means that displays, and thus windowed documents represented by these displays, maintain the state of their content even when not in use, which represents a form of fixity of content.

4.8.5 Strengths and Limitations of the Current Prototype

Two main strengths set apart the conductive dot pattern technique from other systems tracking piles: the absence of a specialized desk setup, and the ability to track documents in any order and position. While many prior systems are vision-based [28,40,52], or tabletop-based [50, 80, 81], DisplayStacks provides tracking hardware both independent from the desk and self-contained in each document. In addition, it can track the movements of one or multiple displays at once, in any order, an improvement on previous work [6, 52, 65]. While it does require specialized circuitry on each display, the addition of those components is reasonable at this time as we have not reached ubiquity of flexible displays.

However, the conductive dot pattern and bezel limit gestures to be discrete, and limit the number of orientations and positions available. A prefabricated circuit with a denser
concentration of conductive dots and zones could provide finer grained information that computes the position and orientation of displays in a stack more precisely. This could allow for continuous rather than discrete occlusion detection. Similarly, a robust alternative to conductive dots could alleviate the issue of tracking accuracy. Finally, although three displays are enough to demonstrate each interaction technique, the use of a limited number of displays restricts combinations of interaction techniques, as well as may not reflect real world piles.

Another core limitation of this work resides in the physical restrictions of the prototype, mainly based on restrictions in the display technology. The design of the flexible display requires the presence of a bezel to power the pixels, leaving a gap between displays during overlap or collocation. This impacts the illusion of increased real estate. In addition, current flexible display prototypes cannot be bent everywhere, due to the presence of rigid electronics. This reduces the pallet of bend gestures available for consideration. Another critical restriction is that our displays are currently tethered for technical reasons. An ideal version of our system would be untethered, containing the electronics and batteries in a flexible sheet of material.

4.8.6 Future Applications
Future applications of an untethered version of DisplayStacks would exist in mobile scenarios. By carrying a stack of displays, users can increase their real estate on the fly, e.g., when studying maps [49]. Each display may run its own mobile app, easing multitasking through the use of multiple lightweight displays. E.g., a user might use one display to make notes while holding a videoconference on a fanned display. Interactions between screens can facilitate a light-weight means of moving data between apps or windows, for example to send notes as an attachment to an email may only require tapping the note display onto the display with the reply email. We
therefore need to explore other techniques for creating, transferring and deleting content on paper display devices.

4.9 Summary
We presented DisplayStacks, a system that allows users to interact with stacks of multiple thin-film flexible displays containing digital documents. DisplayStacks introduces tools for organizing digital documents using piles and stacks of physical display windows. The functional prototype is composed of multiple thin-film electrophoretic ink electronic paper displays augmented with conductive dot pattern sensors that detect relative position and orientation of displays within the stack. With this system, we provide users with the ability to combine the benefits of physical manipulation of paper documents with the malleability of electronic content.
Chapter 5

PaperTab: Spatial Interaction Techniques for Multiple Large Thin-Film Displays

This chapter is in part based on [86]

Figure 20. PaperTab with 9 physical windows and (virtual) hot, warm and cold zones.

In the previous chapters, we demonstrated interaction techniques for single and multi-display paper computers with small, mobile form factor displays. In this chapter, we set our sights on developing a paper computer with multiple large 10.7” flexible displays for interacting with digital media. We present PaperTab, a paper computer with large functional touch sensitive flexible electrophoretic displays. PaperTab merges the benefits of working with digital information with the tangibility of paper documents. In PaperTab, each document window is represented as a physical, functional, flexible e-paper screen called a tab. Each tab can show
documents and other digital information at varying resolutions. The location of tabs is tracked on the desk using an electromagnetic tracker. This allows for context-aware operations between tabs and the desk. The desk is divided into 3 proximity-based zones: the hot zone, used for full screen browsing and editing of documents, the warm zone for displaying thumbnail overviews, and the cold zone for filing of documents. Touch and bend sensors in each tab allow users to navigate content. Tabs can also be pointed at one another for focus+context view operations: e.g., documents are opened by pointing a tab at a file icon on a second tab. Bend operations on a tab allow users to navigate content: flicking the top right corner pages forward or back, while bending the tab zooms in or out of the document. We report on a user experience study with 12 participants.

5.1 Introduction

A long-standing debate in user interface research is the tradeoff of benefits between physical and digital user interface objects. In particular, the vision of a physical desktop computing system based on the way office workers use paper documents has been an enduring research goal [12]. One of the reasons for the longevity of paper, according to Sellen and Harper [77], 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 [77]. On the other hand, Graphical User Interfaces (GUIs) provide superior opportunities for on-the-fly electronic manipulation and updating of information over paper. While accepting that malleability is a basic requirement for any user interface, in this chapter, 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, particularly in cases where windows obscure each other; (2) spatial manipulation of windows is defined and limited by screen size and (3) users cannot apply spatial memorization skills for GUI-based information retrieval as effectively as they can in real, physical, environments [40]. One solution is the design of a system that combines tangible, paper-like interactions with digital information (not limited to documents), specifically by embodying windows onto an electronic paper-like medium.

The idea of providing paper-based interaction with digital information is far from new: it was the core idea behind Memex [12] which inspired the GUI. Wellner’s DigitalDesk [89] was one of the first systems to implement such seamless interaction between physical and digital mediums through digital projection on paper. Since then, many tabletop research projects have explored the coexistence of paper and digital information [37,50]. While these systems provide various affordances of paper, they are often limited in their interactions, and do not take advantage of the spatiality of content beyond the 2D surface of a desk.

In the previous chapter, with DisplayStacks, we made use of ASU’s Bloodhound displays to merge the physical world of paper with the digital world of information via Organic User Interfaces [39]: non-flat, flexible, tactile, high-resolution display interfaces. The displays were sufficiently thin and light to approximate paper-like stacking interactions. In this chapter, we use 10.7” Plastic Logic displays to extend this work by exploring spatial interactions with large displays as seen in DigitalDesk and PaperWindows.

We present PaperTab, an electronic paper computer that allows physical manipulation of digital information using multiple flexible electrophoretic displays embodied on a physical desk (see Figure 20). Documents in PaperTab combine the malleability of electronic windows with the tactile-kinesthetic and 3D spatial manipulability of paper documents. In PaperTab, each graphical
window is represented by a fully functional (paper-sized) 10.7” Plastic Logic thin-film high resolution flexible electrophoretic display.

5.1.1 Contributions

In this chapter, we contribute one of the first paper computers with multiple functional, and large touch-sensitive thin-film flexible electrophoretic displays. We also contribute a functional physical windowing system with interaction techniques for zone and focus+context interactions. Zone interactions are based on the proximity of each display to the user. PaperTab determines the 6 DOF location and orientation of each display on the desk through an electro-magnetic sensor mounted on the back of the displays. Locations of displays are categorized into hot zones, used

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for active editing, warm zones for temporary storage, or cold zones for long-term storage [77]. Each display has a transparent flexible capacitive touch input layer. This is used for focus+context interactions [8], which allow users to point with one flexible display at coordinates within a second flexible display, e.g., to pop up a magic lens [10]. We contribute a user experience study, examining several representative tasks in which data was moved within and between multiple flexible displays.

### 5.2 PaperTab

PaperTab is a paper computer made of many flexible thin-film electrophoretic displays that can be held in the hands or placed on a physical desk. The displays serve as electronic paper windows into computer documents. In PaperTab, each display corresponds in functionality to one window on a GUI. We call these physical instantiations of one window per display a tab (see Figure 21). Users can interact with the system by moving tabs around their desk, and can navigate and edit information on a tab using touch input and simple bend operations [55]. Users can also use a tab as a magic lens that points at another tab, allowing them to pop up information on the top tab detailing items displayed on the underlying tab.

### 5.3 Design Rationale

We use multiple piles to manage different task contexts with paper documents. In GUIs, we use overlapping windows for handling multiple information contexts. GUI windows support easy scalability of information as they change from a single document view to a group of document icons to groups of folders. With DisplayStacks we explored interaction techniques with a single pile of documents. With PaperTab, we embrace the "window" of the GUI to scale up the amount of information we can interact with, using paper computers.
The design constraints outlined in section 4.5 (bending as an input metaphor; two-handed use; thinness and low-mass; input) apply to the design of PaperTab. In addition, when designing PaperTab, we focused on developing context-aware window management techniques that would allow for interactions with many documents represented on many physical displays, through relative movement of those displays. We used the following design criteria:

5.3.1 1 Window = 1 Display
The basic token in PaperTab is the tab: each GUI window is a physical display. The main reason for this was that it allows for virtually unlimited screen real estate spread over large work areas. PaperTab is document centered, and requires a physical instantiation of each document on a tab. While tabs can have multiple documents, and documents on tabs can have multiple pages, at no point is a document not represented on a tab. This allows users to move digital documents by moving tabs physically and tangibly through spatial arrangement on their desk.

5.3.2 Location Awareness
Each tab is aware of its own location on the desk, as well as relative to and within other tabs. This allows smart context-aware operations between tabs that depend on how close they are to the user or to other tabs. In addition, we can leverage the known location of each tab on the desk for encoding and/or triggering specific spatial context of use.

5.3.3 Spatial Proximity = Resolution
Because screen real estate is limited in desktop GUIs, windows are typically stacked on the desktop in a virtual z dimension, obscuring one another. Since in PaperTab real estate is not limited to a single display, or even a single desktop, we designed tabs to vary the resolution of a document’s information based on physical proximity to the user [77]. Tabs that are furthest away
from the user represent file thumbnails that are not in use. Documents in the middle zones represent overviews.

5.3.4 Spatial Proximity = Focus
The use of proximity to activate document views also required a redefinition of the concept of top or focus window. Here too, we used the metaphor of proximity: the closer a display is to the user, the more focus we expect it to receive and the more receptive to input it becomes. According to Sellen and Harper [77], users often use proximity when dealing with paper documents. Hot paper documents are in immediate use, serve multiple concurrent purposes and are in close proximity to the user. Warm paper documents have served or are about to serve an immediate need, but should not be in the way of handling hot documents. Cold paper documents represent archived documents that are not in immediate use, and are typically filed away from the user. We translated these notions of hot, warm, and cold zones into a proxemics design [31] in which tabs are brought in and out of task focus by physically moving them towards or away from the user. Sellen and Harper [77] also suggest that to allow for easy multitasking, every document that is within close proximity of the user should be active for input, with the most active windows being the ones held by the user.

5.3.5 Movability = Mass and Volume
The effectiveness of having displays as windows is greatly reduced by the weight of the display [23]. Moving a stack of 10 tablets around one’s desk does not rival the efficiency of moving paper documents. To move tabs around with the greatest efficiency, we believe it is important that they are made of the most lightweight displays available.
5.3.6 Display = Pointing Device

We were greatly inspired by work on focus+context displays [8], magic lenses [10] and spatially aware computing in the design of our system. As with lenses in GUIs, users should be able to use one tab to navigate content displayed on another tab.

5.4 Interaction Techniques

In this chapter, we focused the design of interaction techniques for PaperTab on the problem of windowing in a system with many displays, where each display is the functional equivalent of a single GUI window. One challenge was that unlike GUIs, no user interface exists in the space.
between windows. This means the user interface lives among a collection of displays, rather than just within a single display. As such, we considered interactions with tabs as pertaining to one of two types: zone interactions and focus+context interactions.

5.4.1 Zone Interactions

In traditional GUIs, windows are organized using a stacking metaphor: the most proximate window is the top or focus window, which contains the active document that the user is working on. Since in PaperTab, windows are laid out on a physical desk with more real estate, stacking of windows need not be the dominant metaphor for task focus. Rather, and according to Sellen and Harper’s analysis of paper document use, the focus or activity level of a window is determined by the proximity of a tab to the user [77]. Figure 22 shows PaperTab’s three zones of proximity to the user, each pertaining to a different 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).

5.4.1.1 Hot Zone

In this zone, tabs are either held by the user, or within immediate hand’s reach of the user. They are the equivalent of the top window in GUIs. They contain active documents editable by the user via touch input or keyboard. When a tab is moved into the hot zone a small LED in the top left corner of the display turns green indicating they have become editable. When displays are moved to the hot zone is there no change to the view resolution. This is only true for documents moved to the hot zone, and the reason is to allow users to examine the contents of warm and cold tabs without changing their view. When tabs are moved in the other direction, i.e., from the hot zone to the warm zone, their view changes to a thumbnail overview of the document. When they are moved to a cold zone, the document closes to show a file icon. This is the equivalent of closing a
window in a GUI. Tabs remain hot until the user releases them in a warm or cold zone. Users can use touch or bend navigation to change view in the hot zone. E.g., in the hot zone, users can go from a thumbnail overview to a full screen view by bending the sides of the display outwards.

5.4.1.2 Warm Zone
In this zone, tabs 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. As such, documents contained in warm tabs are locked, and not directly editable by the user. This allows them to be handled and placed in piles without the risk of spurious input. They do, however, respond to external events such as alerts, incoming files, emails, or edits by remote users. Whenever a tab is moved to the warm zone this is indicated by an LED in the top left corner of the display turning amber. When a tab is moved from a cold zone to the warm zone, the documents in the cold tab are opened into tabs displaying thumbnail overviews. This allows a convenient way of opening up multiple documents onto a single tab. These tabs can be selected through touch when the tab is picked up. When the tab is moved back to the cold zone, the tabs close to show a file icon. When a hot tab is moved to the warm zone, this causes the tab to show the thumbnail overview of its document. For example, if the user is browsing a full screen photo in an album, moving the display into the warm zone would cause it to display thumbnails of all photos in the album.

5.4.1.3 Cold Zone
In this zone, tabs are just outside of arm’s reach of the user, yet easily accessible by leaning or reaching forward over the desk. Cold tabs allow storage of documents out of the way of the active task. They are equivalent to file folders in GUI filing systems. The cold zone provides users with an easy way to file and retrieve documents. Filed folders are not editable and only respond to touches by other tabs. When a tab is moved into the cold zone, the LED in the top left corner of
the display turns off, but it continues to respond to touch input. The display of a tab in the cold zone is powered off when not interacted with and, similar to printed documents, does not consume energy. Displays are powered back on when they are picked up, touched by another tab, or updated externally.

5.4.1.4 Document Notifications
When a document on a warm tab receives an external update, its LED starts flashing amber to notify the user. E.g., a user may keep her E-mail Inbox in a warm tab displaying a list of recent
emails. When a new email arrives, this tab starts blinking. Users can open the last received email by moving the tab with the Inbox document into the hot zone and touching the email. Moving the Inbox back into the warm zone closes the current email and moves the window back to its original list overview. The LED notification stops blinking when the tab is touched.

5.4.2 Focus+Context Interactions

Multi-display interactions provide convenient focus+context navigation of content on hot, warm, or cold tabs via a second, hot tab. When a hot tab is moved into another zone during this interaction, it remains hot as long as the user holds the tab. When a user points the top left corner of the hot tab onto the thumbnail on the underlying warm or cold tab, the hot tab shows a full screen preview of the thumbnail. This is the equivalent of magic lenses [10], hyperlink previews, or contextual menus in GUIs. After previewing the item, the user can move it permanently onto the hot tab by lifting it and pulling it into the hot zone, preserving the detailed view. Users can also point within hot tabs (see Figure 23). E.g., pointing at a URL in a document on one hot tab shows a full-screen preview of the webpage on the top hot tab. Pointing at a location on a map or an item in a book’s table of contents may pop up a linked page on the second screen. This technique provides an interesting alternative to the Pick and Drop technique [72], for multiple displays.

5.4.2.1 Filing and Opening Documents

Document files are opened by pointing an empty tab at a list of document file icons represented on a cold zone folder. During pointing, the hot tab shows a thumbnail overview of the contents of the file document. In the cold zone, file icons can be moved between folders by pointing at their thumbnail, picking them up onto the hot tab, and then tapping a third tab. When a user points with
a hot tab at an empty space within a file folder in the cold zone, its document is closed and the thumbnail is moved into the filing folder. This closes the tab, emptying its screen.

5.4.2.2 Moving Data Objects

Users can also copy or move documents and data objects within documents via this technique. This action is equivalent to using a GUI clipboard for cutting, copying and pasting files. For example, this way users can add an attachment to an email displayed on one tab by tapping its empty space with an image or a document on another tab. Alternatively, users can move a data object between two tabs by placing them adjacent to each other, then dragging the data object from one display to the other with a finger.
5.4.2.3 Keyboard Input

Users can type on a standard wireless Bluetooth keyboard to edit text. The location of the keyboard on the desk is tracked, and input is automatically routed to the document that is closest to the keyboard. Users can tie the keyboard to a tab by hitting a function key on the keyboard while the keyboard is adjacent to it. When users subsequently move the tab, input continues to be directed to it.

5.4.2.4 Bend Interactions

Individual tabs respond to bends on the top left and right corners of the display, as well as the full display. According to Lahey et al. [55] users have a preference for top corner bends over bottom corner bends. Building upon these results, we implemented the following bend gestures for PaperTab: Bidirectional top-right corner bends for navigation, and bidirectional top-left corner bends.
bends for application-specific tasks (e.g., the tear gesture to unlink two collocated tabs, or to reply to an email—see Figure 24). Full display bends are used for zooming in and zooming out.

A downward top-right corner bend selects the next tabbed document or pages forward, while an upward top-right corner bend pages back [92]. Bends are also used to scroll through lists that are larger than fit the physical display. Bends performed across two tabs copy the selected information from the top to the bottom tab. Users can stack tabs and bend the top right corners inwards with a single gesture to create a file folder containing the contents of each of the tabs: the folder appears on the top tab and the other tabs become empty.

5.4.2.5 Colocation of Tabs
If an empty tab is placed directly adjacent to and slightly overlapping with a tab, the system responds by creating a larger view of the original document across the two displays [36,40]. Items can be moved or copied between two collocated tabs by dragging them via touch (see Figure 25). If collocated tabs are moved away from each other, they will display a subset of the larger graphics environment that is framed by the two displays [24]. This allows browsing of large graphics documents using multiple tabs as magic lenses. E.g., if one tab containing a Google map of a city is collated with another, the map expands to encompass the area next to it. If the second tab is now moved away, the view of that tab will automatically scroll to the relative distance from the original tab, thus revealing other cities. This can be useful when planning detailed routes between an origin and destination city. This feature is also useful for browsing large graphical documents, such as architectural drawings, across the entire desk space without zooming. Collocated tabs are disconnected again using a tear gesture. This consists of bending the top left corner of right tab upwards while moving the display upwards. Upon tearing, two separate
documents are created, each containing the data objects on display. In the case of the map example, this would, e.g., produce one tab with the origin city, and one with the destination city.

5.4.3 Summary of Interaction Techniques

To summarize, PaperTab’s interaction techniques include the following key elements:

**Zones:** Tabs are either hot (editable), warm, or cold (off) depending on their distance to the user.

**Document-centrism:** A tab may display no documents, part of a document, a single document, or multiple documents (tabbed).

**Varying detail:** The level of detail displayed by tabs changes when moved between zones. The only exception is when tabs are moved directly to the hot zone, in which case there is no change of view.

**Focus+Context:** The tip of a tab can be pointed at the contents of other tab to show more detailed views of data objects or files. Tabs can also be collocated to create larger views.

**Input:** Interactions with tabs occur through touch, keyboard, bending, proximity (to other tabs, to the desk, and to the user), as well as by pointing between two tabs.

5.5 Implementation

The primary goal of building PaperTab prototype was to realize a functioning multi-display paper computer, preferably with large displays. In addition, we wanted the prototype to be robust enough to evaluate the associated interaction techniques both qualitatively and quantitatively. We followed an iterative design approach.
We designed our first prototype with the 3.7" 'Bloodhound' displays as larger display configurations were unavailable. We built upon the DisplayStacks prototype to support PaperTab’s interaction techniques.

We discarded the conductive sensor layer and designed a new flexible sensor layer for each tab. The layer consisted of a flexible PCB with 48 miniature infrared (IR) proximity sensors laid out in 8×6 grid pattern (Figure 26, right). In addition, we designed an interaction surface with...
passive IR reflective patterns on them. This arrangement of sensors and surface patterns allowed each tab to approximately sense its location when placed on the interaction surface (Figure 26, left.) It also solved the accuracy issues, plaguing the conductive dots of DisplayStacks, when tracking display arrangements in stacks.

We implemented the new interaction techniques by extending the DisplayStacks architecture. However, there were limitations with this prototype. Firstly, the prototype continued to be plagued by the limited robustness of the displays being used. In addition, the IR sensor grid, while supporting zone interactions and stacking interactions, could not uniquely identify an underlying display being pointed at. Lastly, the Processing sketch did not scale well with the increasing information load when handling multiple displays and more sensor data.
Our challenges with this prototype stressed the need for us to focus on larger and more robust displays, as well as a better way to track the displays in 3D.

### 5.5.2 Prototype 2: Large Displays with limited tethering

For our second prototype, we procured Plastic Logic 10.7” displays driven by a portable processor with wireless connectivity running Android OS. The processor was powered by a detachable 4 mm thin battery. While the underlying electronics was rigid, we designed a custom flexible body to mount the electronics with the battery to the back of the flexible display. Each display prototype was 6 mm thick and weighed 70g. Due to the rigidity of the processor board, each tab could be flexed to only 30º in both directions.

We attached sensors for full 3D tracking of displays, bend sensing, and touch sensing (described in-detail later.) We designed a distributed software architecture where each tab managed its own processing and display-driver with an Android application. The tabs passed messages between them for managing different interactions. One of the tabs played the role of the arbiter that had complete awareness of the state of all tabs at any given time. However, due to the limitations in connectivity, a PC was used for interfacing with the sensors. While each display and processor operated wirelessly, sensors in each tab were still tethered to the PC.

There were various limitations of this version of the prototype: (1) the rigid electronics beneath each tab affected the bend interactions (see Figure 27); (2) the thickness of each tab was not suitable for stacking and pointing tasks; (3) the distributed software architecture made it challenging to quickly deploy applications and to debug them.
We describe the details of our final prototype in the next section. We chose to retain flexibility, thinness, and low mass of the displays in our final prototype by offloading the processor and power supply from the tabs using long ribbon cables.

### 5.5.3 Final Prototype

Each tab is a dumb terminal that communicates with the host PC, through an offloaded driver board, for UI updates, sensor input and to coordinate data exchanges with other tabs. Tabs are tethered to a host PC, an 8-Core MacPro running Windows 7 that is placed underneath the desk. Figure 28 shows an exploded view of a tab consisting of 4 flexible layers. The top layer consists of a flexible capacitive touchscreen. The second layer contains the flexible electrophoretic display. The third sensor layer provides tracking, while the fourth senses bending of the corners of the display and also consists of a circuit that allows capacitive coupling between tabs for pointing. Each tab is approximately 0.7 \( \text{mm} \) thick and weighs approximately 30 \( \text{g} \).
Table 2. Plastic Logic Flexible Electrophoretic Ink Display Properties.

<table>
<thead>
<tr>
<th>Display Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Display Area Dimensions</td>
<td>217.6×163.2 mm (i.e. 10.7” diagonal)</td>
</tr>
<tr>
<td>Outer Display Dimensions</td>
<td>246.6×189.7 mm (i.e. 12.25” diagonal)</td>
</tr>
<tr>
<td>Resolution</td>
<td>SXGA- (1280×960 px)</td>
</tr>
<tr>
<td>Weight</td>
<td>20 g</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Bend Radius</td>
<td>50 mm</td>
</tr>
</tbody>
</table>

5.5.4 Layer 1: Flexible Touch Input
The first layer consists of a flexible, thin-film, transparent Zytronic\(^8\) capacitive touch screen, 10” in size diagonally. This layer is connected to a host PC with a ribbon cable, via which it issues touch events to the application software running on the tab. In order to enable multi-display pointing using the touch sensor, we developed a capacitive circuit that, when the tab is held by the hand, transfers the user’s capacitance to a soldered tip on the top left corner of the tab. This activates touch events upon one tab touching another.

5.5.5 Layer 2: Flexible Electrophoretic Display
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 1280×960 pixels, with a full-screen refresh rate of 700 ms (see Table 2 for detailed display specifications.) The display is connected to a custom Plastic Logic driver board, underneath the desk, via ribbon cables. This board is connected over USB to a PC that controls the system logic and the user interface.

\(^8\) Zytronic, PLC. http://www.zytronic.co.uk
5.5.6 Layer 3: 6 DOF Location and Orientation Tracking

An electromagnetic sensor mounted on each tab allows tracking of location and orientation relative to the other tabs, as well as the desk and the user. It consists of a small trakSTAR\textsuperscript{9} sensor probe that is attached via a wire to a processor box placed underneath the desk. While the displays could easily be tracked wirelessly via computer vision systems available to the authors (e.g., Vicon, Kinect) \cite{40}, we chose to track them using a wired configuration in the current prototype because of the following reasons. Firstly, computer vision systems suffer from occlusion, making it difficult to track tabs when they overlap. Secondly, we believe an electromagnetic solution to provide a better value proposition for production models. Commercial electromagnetic trackers already support tracking of wireless markers (e.g. Polhemus\textsuperscript{10}.) However, these markers are currently bulky and unsuitable for thin-film applications. It is conceivable that lightweight and wireless electromagnetic trackers will be available in the near future. Finally, the electromagnetic tracker provides greater resolution in all 6 DOF.

5.5.6.1 Hot, Warm and Cold Zone Tracking

Our software translates the 6 DOF coordinates of each tab to determine the location of a tab relative to the user, relative to the desk, and relative to other tabs. A tab is hot when it is lifted from the table, or when it is within arm’s length (70 cm) from the user. A tab is warm when it is on the desk between 70 cm and 110 cm from the user. All other tabs are cold, with their displays powered off. These measurements are based on the affordances of the desk and size of the displays. They can be easily reconfigured to suit different desk sizes and usage patterns. The electromagnetic tracker also determines when tabs are collocated, and tracks the distance between

\textsuperscript{9}Ascension, Inc. trakSTAR. http://www.ascension-tech.com/medical/trakSTAR.php

\textsuperscript{10}Polhemus Electromagnetics. http://polhemus.com/applications/electromagnetics/
them when connected tabs are moved apart. Finally, the electromagnetic tracker determines when tabs are stacked on the basis of their z coordinate.

5.5.7 Layer 4: Bend Sensor Layer
The bend sensitive layer consists of 2 bi-directional Flexpoint bend sensors mounted on a custom-built flexible circuit board mounted directly underneath the display. Bend sensors are connected via a flat ribbon cable to an Arduino Mega prototyping board that communicates with the host PC for processing bends.

5.5.8 Layer 5: Capacitive Grounding Wire (not shown)
The bottom layer features only a small wire connected to a small metal tip that transfers the capacitance of the user’s hand to another tab for the purpose of activating the Zytronic touch film. This is used for focus+context pointing with one tab onto another.

5.5.9 Software
A C# host application on a PC manages the interaction logic for all tabs. Bend sensor input and touch sensor data are processed by the C# application. A trakSTAR processor/emitter mounted underneath the desk preprocesses the 6 DOF sensor data and send coordinates back to the C# host. The processed data from all these sensors are used for determining the state of the system and tracking interactions in real-time.

To provide real-time interactions, the host application maintains multiple dedicated software processor threads. The processor threads manage different tasks for each tab: processing three input streams of data (bend input, touch input, 3D tracker data); managing and updating system states for all tabs; rendering the UI for each tab; and finally pushing the UI to the respective tabs.
5.5.9.1 Input Threads
Each of the different input streams is handled by dedicated thread (one per device per stream.)
Multiple threads help in maintaining the varying interfacing speeds for each sensor. The threads
also manage filtering of noise from the incoming data streams.

5.5.9.2 Interaction Thread
A single interaction thread manages the detection of bend, zone, and pointing gestures using the
filtered sensor data.

5.5.9.3 Tab-State Threads
State of each tab is managed in its own running thread. Sensor input and interactions affect the
state of these threads.

5.5.9.4 UI Threads
Updates to tab-states trigger rendering of updated UI for each tab. The UIs are rendered on the
host PC’s buffer and pushed out to each tab via the driver boards.

5.5.9.5 Debug Thread
To manage and debug this large software, we developed a custom interface for the PC. The
interface provides visual feedback of the state of each display including their 3d coordinates and
error messages.

Threads communicate with each other using custom asynchronous messages. Our host
application ensures real-time update of each tab while providing centralized control to the entire
system. This centralized control of the interaction space simplifies the deployment of new
features as well as debugging despite the increase in processing requirements. Our software
architecture is currently not capable of supporting new tabs added to the system in real-time.
5.6 User Study

We conducted a qualitative user study to elicit user feedback on interacting with PaperTab.

5.6.1 Participants

12 paid volunteers (5 females, 7 males) participated in the study. The participants were between the ages of 21 and 30 (mean 24 years). All of them were right-handed.

5.6.2 Task and Procedure

We first asked each participant to place the tabs on the desk, based upon when they should expect to next interact directly with the display: (1) in a moment (2) within the next few days, and (3) in the next few weeks. The primary purpose for this task was to understand users’ preferred locations for the hot/warm/cold zones. We recorded the positions of the tabs and used them to calibrate the location of the various zones on the desk. Participants were then asked to work on 3 different overall tasks using 3 tabs. Tasks were designed to encourage the use of interactions within and between tabs:

1) **Document Management.** Participants interacted with several PDF documents using between-display (zone interactions, collocation) and within-display (filing, opening documents) interactions. They were asked to perform 3 subtasks: (a) Search for a described artifact (an image or a phrase) from one of three documents, requiring the users to open, navigate, and file documents; (b) Find the total number of images in a document in the warm zone with the help of thumbnails and full screen mode; (c) Collocate displays to compare two pages of a document.

2) **Answering Email.** Participants interacted with the email application using between-display (zone interactions) and within-display (filing, opening documents, moving data objects) interactions. They were asked to perform 3 subtasks: (a) find an email with a
specified attachment by opening different emails using within-display pointing; (b) find requested information from one of the emails in the inbox with the help of an email list displayed in the warm zone; and (c) reply to an email and attach a photo from a second display using within-display pointing.

3) **Route Planning.** Participants used between-display (collocation and panning) and within-display (opening documents) interactions to plan a route using a map. They were asked to perform 3 subtasks: (a) Find a location on the map by opening the map application and panning to the correct area within the map; (b) Collocate two tabs to extend the map view; (c) Pan to a specified location on the extended tab.

Each session began with a 5-minute introduction followed by a 10-minute period during which users freely explored the system. Participants were given instructions on functionality that they did not discover themselves during this period. After performing the tasks, users were asked to rate different interaction techniques for Learnability, Efficiency, Physical Demand and Mental Demand on a 5-point Likert scale (1 Strongly Disagree - 5 Strongly Agree). Their comments were also recorded.
5.7 Results

Participants learned to perform the interactions in less than 5 minutes. We report the mode and frequency of responses for the questionnaire answers. We evaluated these responses using a $\chi^2$ test to confirm positive or negative attitudes. Since our minimal cell count was less than 5, we collapsed data into 2 categories: positive and negative, ignoring neutral responses [18].

Figure 29 summarizes users’ ratings on the Likert scale for different interaction techniques. We report the results for clarity and take the results as trends. Where users agreed on a value, without any variance, we do not report a $\chi^2$ statistic. Overall, users found PaperTab easy to learn (mode=4, frequency=58.33%, $\chi^2(1)=7.364, p=0.007$), efficient (mode=4,
frequency=58.33%), and low in physical demand (mode=1, frequency=41.67%, $\chi^2(1)=5.444$, $p=0.020$) and mental demand (mode=1, frequency=33.33%).

5.7.1 Between-display Interactions

When asked to place tabs on the desk, based upon when they would be used again, for hot and warm zones, participants placed the tabs in locations consistent with our zone interactions. However, 5 participants noted that they would prefer to keep the displays away from the desk for cold zone documents. Participant 12 (P12) proposed stacking a display that would not need to be accessed for several days beneath another display located in the warm zone.

Changing the display view between zones was found to be easy to learn (mode=5, frequency=75%) and efficient (mode=5, frequency=58.33%), not very physically demanding (mode=1, frequency=50%, $\chi^2(1)=4.45$, $p=0.035$), and not very mentally demanding (mode=1, frequency=41.67%, $\chi^2(1)=5.44$, $p=0.020$). Participant 5 (P5) noted: “I liked that when I was pulling it closer it knew I wanted to read in more detail and pulled up the document” and P7: “Once aware of zones, I was at first concerned about moving between them, but I realized that no data is lost and the display changes back when I pick it up again.” P4 and P10 wanted to be able to lock or unlock a display to allow for more control over the zone behavior.

Overlapping displays to extend the viewport was found to be easy to learn (mode=5, frequency =50%, $\chi^2(1)=8.33$, $p=0.004$) and efficient (mode=5, frequency=41.67%), not very physically demanding (mode=1, frequency=50%, $\chi^2(1)=6.4$, $p=0.011$), and not mentally demanding (mode=1, frequency=58.33%). P2, P5, P8, and P10 cited collocation as a feature they would use often. They mentioned that, unlike standard GUIs, enlarging by collocation does not come at the expense of other display content.
5.7.2 Within-display Interactions

Users found that pointing with one tab within another tab for opening and closing documents was easy to learn (mode=5, frequency=100%) and efficient (mode=5, frequency=83.33%), not very physically demanding (mode=1, frequency=50%, $\chi^2(1)=5.33, p=0.021$), and not very mentally demanding (mode=2, frequency=41.67%, $\chi^2(1)=7.36, p=0.007$). Most participants were able to understand how to perform the interactions with minimal prompting. For example, after explaining that tabs could be used to point within other tabs, participants were able to determine, without any further instruction, how to attach documents and also put them back into folders. P1, P5, and P8 noted that they particularly enjoyed this interaction. P5: “I very much enjoyed tapping to attach documents.” However, we also observed that pointing with the edge of a tab was sometimes challenging depending on the location of tabs. The pointing tab sometimes occluded the target tab, requiring the participant to reposition their hand. P3 and P9 suggested that the right corner should also be able to be used as a pointing device.

For moving objects between displays, users found pointing to be easy to learn (mode=5, frequency=75%, $\chi^2(1)=4.45, p=0.035$), efficient (mode=5, frequency=91.67%, $\chi^2(1)=8.33, p=0.004$), not very physically demanding (mode=1, frequency=58.33%, $\chi^2(1)=5.33, p=0.021$), and not very mentally demanding (mode=1, frequency=41.67%, $\chi^2(1)=6.4, p=0.011$). P1, P8, and P12 mentioned that they found pointing to be superior to dragging. P12: “Why should I have to drag when I can point?” Dragging involves friction and often required users to bend over the tab. When prompted for further elaboration, participants noted that pointing with a tab was easier, and generally required less effort.

User feedback suggests that both Between-display and Within-display interactions were easy to learn, efficient, and low on physical and mental demand.
5.7.3 Bend Interactions

Bend interactions were found to be easy to learn (mode=5, frequency=41.67%), efficient (mode=4, frequency=50%), and low in physical demand (mode=1, frequency=41.67%) and mental demand (mode=1, frequency=41.67%). Participants wanted to be able to change the polarity of interactions (bend up to page forward vs. bend down to page forward). 2 participants indicated that they did not prefer to bend the top-left corner and wanted to have most bend interactions confined to the right side of the display. Rather than using bends, P4 proposed having an “Outbox zone” to place emails for sending.

5.8 Discussion

Overall, the results of our user study were in line with our expectations. PaperTab interaction techniques appear easy to learn and do not induce significant physical demands, while achieving low ratings for mental load. One of the most common suggestions from participants trying our prototype is that it should make more extensive use of zones for different document types. For example, a video could be played full screen in the hot zone, paused in the warm zone, and appear as a thumbnail with a description in the cold zone. However, at the same time, users appreciated the one-directionality of view changes for hot tabs. It appears that automated view changes based on proximity are a balancing act of allowing easy overview of information while keeping the user in control of the view.

While our zones were designed with the paper usage pattern in mind, physical paper usage also varies widely with changing contexts. This is supported by user feedback requesting further customization of zones. A stronger support for customization of interactions and appropriation of the tab hardware may increase the usage of paper computers in ad-hoc scenarios and enhance their usefulness.
Feedback from the user study indicated strong preference for pointing with tabs over
dragging via touch. We may want to improve the surface characteristics of the touch film in
future versions.

### 5.8.1 Implications for System Software and Hardware

We explored multiple software and hardware architectures for PaperTab through three different
prototypes. With prototypes 1 and 3, the computation was confined to a centralized hardware, i.e.,
a PC. The displays and the associated driver electronics, decoupled from the underlying
computation, acted as dumb terminals. With this architecture, we were able to deploy and test
system updates faster. In addition, the displays’ physical properties were left unchanged when
testing interaction techniques. In an ideal paper computer, this system architecture would be
beneficial when considering flexible displays as peripheral devices connected to and driven by a
parent device, e.g., a laptop or a tablet.

Prototype 2 was more ambitious with a distributed software and hardware architecture.
The processor, display driver, and power source were self-contained within each tab. One of the
displays played the role of an arbiter. However, computation was distributed. This architecture
was slightly more complicated and increased the time and effort required to deploy and test
system updates. In addition, owing to current hardware limitations, the prototype's flexibility was
less than ideal.

A centralized system architecture may be more practical and economical than a
distributed one for building paper computers in the near future. This approach offloads the
computation and the bulk of the power requirements onto a parent device. However, such a paper
computer’s functioning would always be limited by the computational capabilities of its parent
device.
We consider a fully distributed architecture to be ideal for a paper computer system as it promises a truly untethered and independent use of paper computers. Despite the increased complexity of such an architecture, a truly distributed system could support graceful degradation of its interaction and computation capabilities. If one of the tabs stopped functioning, this would not impact the functioning of the other functioning tabs. A user could continue to work with even a single tab. Such a distributed approach is contingent on advances in flexible electronics, lightweight battery technology, and advanced software tools to build distributed applications.

All our prototypes suffer from wired tethering. While tethering of tabs appeared awkward to users, it generally did not seem to interfere with interacting with the system. Our use of tethered electromagnetic tracker also limited the portability of the system. However, precise tracking of physical objects in a wireless and small form factor continues to be an unsolved engineering challenge. Future versions will remove the need for tethering by introducing lightweight processors attached on the side of each tab (as a rigid handle), and by processing of touch, bend and tracking operations on the tab itself. Advances in organic electronics and nanotechnology will alleviate the issues of accurate sensing, position tracking, and portable power sources in thin-film form factors.

5.9 Summary
In summary, we presented PaperTab, a paper computer with large (10.7”) touch-sensitive, flexible, electrophoretic displays. The displays, augmented with sensors and driver boards, are called tabs. Each tab embodies a single document window. The location of each tab is tracked on a desk using an electromagnetic tracker. Document views are adjusted when the tab is moved between three proximity-based zones. Tabs can be pointed at one another for focus+context
operations, while touch and bend sensors allow users to navigate content. User study results suggest that our interaction techniques are overall easy to learn and less physically demanding.

With PaperTab, we successfully realized our vision of multi-display paper computers with large displays. Fully untethered version of PaperTab would allow us to deploy our system in the ‘wild’ to understand the long-term usage patterns and challenges of paper computers.
Chapter 6

Evaluation of Flexible Display Interactions as Area Cursors and Within-display Pointers

In the previous chapter, we presented PaperTab, a paper computer with large flexible displays. Qualitative feedback of PaperTab interaction techniques indicated a largely positive response to spatial interactions with paper computers for manipulating digital media.

In this chapter, we address a more fundamental question of paper computers: Do paper computers need flexible displays? More specifically, we investigate how mass and flexibility relate to throughput of movement with displays as area cursors.

We conducted three quantitative studies involving three Fitts’ Law [23] tasks with displays of varying mass and flexibility. Fitts’ Law tasks included moving displays as area cursors between point targets on a desk, tapping the corner of one display onto a target on another display, and dragging a target on a display with the corner of another display.

Results suggested that flexible and low mass displays performed better than rigid, high mass displays for between-display interactions. Flexibility was also found to significantly improve performance of pointing within displays, whereas mass negatively affected the accuracy of pointing. Large displays appear unsuitable for dragging tasks. We conclude user interactions with multi-display paper computers appear to significantly benefit from the use of displays that are both lightweight and flexible.

6.1 Introduction

In recent years, paper-inspired user interfaces have received considerable interest [40,89]. Broadly speaking, there have been two approaches towards achieving a more paper-like user
experience: One strand of research has investigated using off-the-shelf hardware, such as tablet PCs (tablets), to implement interaction styles borrowed from, for example, book reading [14,15].

More recently, a second strand of research has focused on creating user interfaces with displays that try to capture some of the physical properties of paper documents, such as their low mass, flexibility and thinness [40,50,55,80,86]. In this thesis, we have focused on the confluence of these two strands of research: the enduring goal of designing paper computers [40,89] – context-aware multi-display physical windowing systems with paper interaction metaphors. In such paper-inspired user interfaces, each display serves the function of a window in a GUI. Using multiple displays, one display for each application or document in use, reduces the need for windowing, which was designed for managing multiple tasks on a single display. According to O’Hara and Sellen [70], benefits of paper-like computers may include the ability to multitask more effectively by allowing concurrent access to information on multiple displays. The theory of distributed cognition [41] supports this view and shows how we reduce mental load by using physical objects around us in problem solving. However, neither the effectiveness, nor the efficiency of multi-display paper computers has been empirically established. Clearly, moving weighty tablets around on a desk is not as efficient as moving a mouse pointer between windows in a GUI?

6.1.1 Do Paper Computers Need Flexible Displays?

A question that has been unanswered is whether multi-display paper computers would benefit from the use of flexible displays, or whether traditional tablet form factors would suffice. Previous Fitts’ Law studies with flexible displays have focused on the interactions on a display surface. Dijkstra et al. [20] have shown that while flexibility can negatively affect touch performance on the surface of flexible displays, users can easily increase the rigidity of a flexible
display via structural holds. Conversely, the effect of mass on pointing efficiency has been well established during the first experiments by Fitts [23]. It could be argued that in multi-display environments, where users move many physical displays around a desk many times, displays that are both flexible and lightweight are desirable. Our motivation for this work was to investigate the two parameters – flexibility and mass – in isolation and establish their individual effect on users moving electronic paper displays. For this, we abstracted the interaction techniques presented in PaperTab [86].

As seen in the previous chapter, PaperTab introduced two classes of interaction techniques:

1. In Between-display interactions, displays contextualize content based on their position relative to each other and relative to the user. Collocating, overlapping and proximity-based interactions are examples of between-display interactions.

2. In Within-display interactions, the tip of one display is used to point at a graphics object on another display, as if the tip was a cursor. Contextual view pop-outs and menu selection are examples of such Within-display interactions.

Between-display and Within-display pointing operations constituted the core tasks for our study.

6.1.2 Contribution

This chapter presents three quantitative studies. Our studies attempt to answer a fundamental question, i.e., that of the effect of mass and flexibility to the throughput of movement with displays as area cursors. We conducted a first Fitts’ law experiment in which we considered each hardware display as an area cursor [48], used to select a point target that was illuminated on a desk with a laser. The objective was to ascertain the Index of Performance (IP) or throughput of moving displays of different mass and flexibility around on a desk as if they were an area cursor. Results show that both flexibility and low mass of the display have a significant and independent
positive effect on $IP$ of such Between-display interactions. A second Fitts’ Law experiment established the $IP$ for tapping with the tip of one display between two targets on a second display (Within-display interactions). Here too, results show that increased flexibility significantly increased performance. Increased mass negatively affected error rates. Our third Fitts’ Law experiment involved a dragging task. Here, the tip of a display was used as a cursor to perform dragging task on another display. Comparison of the $IP$s for different displays indicates that 10.7” large paper-sized displays may be suboptimal when using the tip of the display for dragging. Overall, results suggest that there are clear benefits for deploying displays in multi-display paper computers that are both lightweight and flexible. Note that our baseline, a paper sheet, appeared to show lower performance than the flexible display for the first Fitts’ Law experiment. This suggests that there may be some optimal level of flexibility and/or mass, and that displays beyond such level are not optimal for multi-display pointing. Overall, results suggest that there are clear benefits for deploying displays in multi-display paper computers that are both lightweight and flexible. Note that our baseline, a paper sheet, appeared to show lower performance than the flexible display for the first Fitts’ Law experiment. This suggests that there may be some optimal level of flexibility and/or mass, and that displays beyond such level are not optimal for multi-display pointing.

6.2 Spatial Interactions with Flexible Displays

To empirically evaluate the efficiency of spatial interactions with flexible displays, we chose to abstract the Between-display and Within-display interactions to basic actions of a) moving tabs between point targets on a desk and b) pointing with one tab at a target on a second tab.
6.2.1 Flexible Displays as Area Cursors
Spatial interactions, such as panning, stacking, and collocation, can be modeled as pointing tasks wherein displays function as area cursors. For example, consider stacking a display on a stationary display. The center of the stationary display acts as the point target to be selected. The center of the moving display acts as the center of the area cursor. The diameter of this cursor is determined by the precision required (or the amount of error allowed) in the stacking operation.

The partial occlusion of the underlying target by the moving display asserts the moving display's role as the area cursor (in contrast to modeling it as a point cursor).

6.2.2 Flexible Displays as Pointing Devices
Within-display interactions can be modeled as pointing tasks in which the tip of a flexible display acts as a cursor. The main target width in this pointing task would be defined by the boundary of the target display, making it difficult to provide an appropriate range of IDs. To address this, we designed for a range of smaller rectangular targets to be shown within the target display to create a variety of widths.

We used the above operationalization to conduct three Fitts’ Law studies: a reciprocal tapping task using displays of varying mass and flexibility as area cursors; a reciprocal tapping task using displays as pointers; and a dragging task using displays as pointers. We describe these three Fitts’ Law studies in the following sections.

6.3 Study 1: Throughput of Between-display Interactions
Study 1 focused on empirically establishing the throughput of between-display interactions. We first studied the effects of flexibility and mass of displays on the IP of tapping them between two point targets on a desk.
**H1.** Our first hypothesis was straightforward as it was predicted by Fitts [23]: that displays with a lower mass have a higher IP when used in a pointing task than displays with a higher mass.

**H2.** Our second hypothesis was less straightforward: that flexibility also increases the IP in this task. Our reasoning behind this was that displays that do not dynamically conform to the ergonomics of the hand may constrain hand motion, and thus throughput.

### 6.3.1 Procedure

We asked participants to tap displays of varying mass and flexibility between two point targets of varying amplitudes. Participants performed the Fitts’ reciprocal tapping task using the Prince Technique [48], in which the cursor is a circle of varying width (diameter) shown on the display, and the targets are two laser points projected on the desk. Participants were asked to iteratively tap the display between the two point targets on the desk as fast and as accurately as possible. This was repeated 16 times, the first hit being recorded only for end point data, recording data points for 15 taps. A hit was recorded when the display or a part of the display was touching the table such that the target point was within the area cursor for at least 50 ms. An error occurred when the target point was outside the cursor, or was not within the cursor for at least 50 ms, in which case participants were provided with an auditory beep. The apparatus was calibrated to account for varying thicknesses of different display types. This ensured consistent tracking for all display conditions.

### 6.3.2 Measurements

Dependent variables included Movement Time (MT) and Error Rate. MT was defined as the overall time between displaying a target and a successful hit within that target. Error rate was
defined as the number of hits outside this target area, and reported as a percentage of trials. We also logged movement End Points (EP), the actual target hit point so as to correct for effective Index of Difficulty (IDe).

6.3.3 Participants
12 paid volunteers (9 females, 3 males) participated in the study. The participants were between the ages of 19 and 45 (mean 22.8 years). All of them were right-handed and performed the experiment with their dominant hand.
6.3.4 Experimental Design and Index of Difficulty

We used a within-subjects repeated measures design with 2 fully factorial independent variables: *Flexibility* (2 levels) and *Mass* (2 levels). We used 4 target amplitudes (150, 300, 600, 1200 mm) fully crossed with 3 area cursor widths (30, 60, 120 mm) resulting in 12 Indices of Difficulty (6 unique IDs: 1.17, 1.81, 2.58, 3.46, 4.39, 5.36). Each of these A-W pairs was performed with all display types. The order of A-W pairs was randomized for each display condition. We also counterbalanced the order of the displays for each participant. The experiment was performed in a single sitting.

6.3.5 Display Factors: Flexibility and Mass

We used a 10.7” Plastic Logic (PL) flexible display (constituting a *Flexible*, low *Mass* condition) and an iPad 2 tablet (constituting a *Rigid*, high *Mass* condition). We then created rigid and flexible versions of these displays (Figure 30). To constitute the *Rigid*, low *Mass* display, we reinforced the PL display with a rigid sheet of carbon-fiber reinforced plastic (CFRP). For the *Flexible*, high *Mass* display (flexible tablet), we used a flexible silicone pad cut to weigh the same as the iPad 2.

We also included a sheet of paper as a condition for baseline comparison purposes. To avoid differences in appearance between displays, we affixed flexible displays on top of the iPad and flexible tablets, such that all conditions except the paper condition used an actual flexible display to show the area cursor. In the paper condition, area cursors were printed onto the paper sheets.

We borrowed the measurement Bend Radius from flexible display manufacturers [46] to define the *Flexibility* of the displays in our flexible conditions. Bend Radius—also a measure used to rate fiber-optic cables—is the minimum radius of the inner curvature of a surface up to
which it can be bent without breakage or creasing [66]. Low and high Mass flexible conditions had a bend radius of \( \approx 50 \text{ mm} \). The paper sheets had a bend radius of \( \approx 1 \text{ mm} \).

The Mass of the displays was 83g for low Mass conditions, 661g for high Mass conditions, and 3g for paper. The weight of the CFRP sheet in the Rigid, low Mass condition, was compensated for in the Flexible condition by padding the back of the flexible display with a few sheets of paper. While the thicknesses of the Flexible and Rigid displays, for the high Mass condition were identical at 9.1 mm, the Flexible and Rigid displays differed slightly in thickness in the low mass condition with 0.8 mm and 1.4 mm respectively.
6.3.6 Apparatus

Participants were seated in front of a 107 cm × 92 cm (42” × 36”) desk. In Flexible conditions, all electronics were mounted off the display (Figure 31). Flexible displays were preloaded with targets on-screen and disconnected from their respective driver boards. The displays were reconnected and targets were changed on them after completion of each condition. Although the flat ribbon cables connecting the driver boards with the displays are flexible and very low in mass (10g), we chose to use this method so movement was not obstructed in any way. While we realize the inclusion of electronics in the Rigid, high Mass condition may be seen as an unfair
disadvantage, the electronics simply constituted a weight factor. This also aligns with our vision of lightweight flexible electronics embedded in future devices.

6.3.7 Location Measurement Hardware and Software

The interaction space was tracked using a Vicon\textsuperscript{11} motion tracking system. The motion tracking cameras (see Figure 32.a) were calibrated for the required interaction space increasing the accuracy of tracking in the interaction space to 0.2 mm. All of the displays were augmented with a 10 mm diameter flat circular IR reflective marker at their center (see Figure 31). This was used

\textsuperscript{11} Vicon Motion Capture Systems. https://www.vicon.com/
to detect when the circular cursor hit the target, so as to record \(MT\) and \(EP\). A Mac Pro computer with custom software written in C# was used for administering the conditions of the experiment:

- Determining the next device and experiment condition
- Tracking the displays using data from the motion tracker
- Switching targets
- Detecting target hits/misses
- Providing auditory feedback for the participants
- Recording the data for further analysis.
- Running simple data analysis algorithms for the gathered data
- Generating tabulated data as an input for Statistics software (for final analysis)

6.3.8 Target Points

To indicate visually the location of the target points on the desk, we mounted 8 red visible light laser pointers (see Figure 32.b) 1m above the desk, illuminating the target points (Figure 32.c) vertically. With this setup, participants were able to locate the targets even when they were hovering over them. The lasers did not interfere with the motion tracker measurements. Flat wooden boards were precisely etched with a laser cutter for marking the target points. These points were used for aligning the laser beams to accurately illuminate the targets. The lasers interfaced with the experiment program via an Arduino Mega microcontroller connected to the Mac Pro. Different amplitudes between targets were presented by turning on or off different pairs of lasers.
Table 3. Fitts’ Law Experiment 1 (Between-display interactions): Mean Effective Index of Performance (in bits/s) and standard error (s.e.) for different display types.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Paper</th>
<th>Flexible Low Mass</th>
<th>Rigid Low Mass</th>
<th>Flexible High Mass</th>
<th>Rigid High Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$IP$ (s.e.)</td>
<td>5.64 (.34)</td>
<td>6.44 (.42)</td>
<td>5.94 (.37)</td>
<td>5.60 (.41)</td>
<td>4.96 (.30)</td>
</tr>
<tr>
<td>Error</td>
<td>1.20%</td>
<td>.83%</td>
<td>.69%</td>
<td>1.16%</td>
<td>.60%</td>
</tr>
<tr>
<td>Model</td>
<td>-56.33 + 203.43*ID ($r^2=.79$)</td>
<td>-49.30 + 178.33*ID ($r^2=.77$)</td>
<td>-23.72 + 184.11*ID ($r^2=.74$)</td>
<td>-144.16 + 230.50*ID ($r^2=.77$)</td>
<td>-81.32 + 234.80*ID ($r^2=.80$)</td>
</tr>
</tbody>
</table>

6.3.9 Analysis: Index of Performance

We calculated the $IP$ of each device, using the mean of means method [78]. For each condition, per device, per participant, the effective widths ($W_e$) and effective amplitudes ($A_e$) were computed using the collected end-point data, deriving an effective Index of Difficulty ($ID_e$). $IP$ was calculated by applying Shannon’s formulation to the average movement time ($MT$) and $ID_e$ for each condition. The resulting $IP$ values were averaged over conditions and participants to obtain the overall effective Index of Performance ($IP_e$) of each device. To calculate slope and intercept, a similar approach was used: Regression analysis on the average movement times and effective $ID$s (per participant, per device) provided the values of slope ($b$), intercept ($a$) and $r^2$ for graphing purposes. These values were averaged over all participants.
6.4 Study 1: Results

Table 3 summarizes the results for $IP_e$. The effective $IP_e$ for flexible low mass condition was 6.44 bits/s (standard error = .42). $IP_e$ for rigid low mass condition was 5.94 bits/s (s.e. = .37). $IP_e$ for flexible high mass condition was 5.60 bits/s (s.e. = .41). $IP_e$ for rigid high mass condition was
4.96 bits/s (s.e. = .30). \( IP_e \) for paper was 5.64 bits/s (s.e. = .34). We performed a two-way repeated-measures Analysis of Variance (ANOVA) on the \( IP \) scores of these four conditions. We omitted the paper condition from the two-way ANOVA since it did not have a fully factorial rigid counterpart. Results show that there is a significant effect of \( Flexibility \) on \( IP \) (\( F_{1,11} = 19.64, p=.001 \)), with flexible devices obtaining a significantly higher performance. We also found a significant effect of \( Mass \) on \( IP \) (\( F_{1,11} = 46.82, p<.001 \)), with devices of low \( Mass \) obtaining a significantly higher performance. There was no significant interaction effect between \( Flexibility \) and \( Mass \) (\( F_{1,11} = .46, p=.513 \)).

6.4.1 Paper vs. Flexible Display
We conducted one planned paired two-tailed t-test to compare the \( IP \) of paper to that of the flexible display. We had no hypothesis for this comparison. We realize this planned comparison would alter the alpha levels of the analysis, and as such report this statistic solely for anecdotal purposes. \( IP \) scores for the paper appeared lower than those of the flexible display condition; \( t(11)=4.157, p = .002 \).

6.4.2 Error Rates
Error rates were low for all devices and well within the 4% tolerance. A two-way ANOVA showed no significant effect of \( Flexibility \) (\( F_{1,11} = 4.28, p=.063 \)) or \( Mass \) (\( F_{1,11} = .21, p=.655 \)) on the error rates for the tapping task. No significant interaction effect between the two factors was observed (\( F_{1,11} = 3.06, p=.108 \)).

6.4.3 Regression Models
Table 3 also presents the regression models for each display type. These models are visualized in Figure 33 per display type. Regressions were performed per subject and then averaged into a
single model per display condition. All regression models had significant correlations ($p<.05$).
The fit of the models in terms of $r^2$ was approximately .8 representing 80% of the variance in
covement time, in all display conditions.

6.5 Study 1: Discussion

The results appear to confirm our hypotheses. Displays with a high *Flexibility* had a higher Index
of Performance than rigid displays (H1). Similarly, displays with low *Mass* had a higher *IP* than
displays with a high *Mass* (H2). An absence of interaction effects suggests that *Mass* was not a
precondition for *Flexibility* to have an effect.

In our post-study questionnaire participant 9 (P9) noted that “*Flexible devices are easier
when moving, but less accurate when hitting the target. The high Mass devices (both rigid and
flexible) are very similar in motion.*” Error rates seem to align with the participant’s views. P2
reported “*Flexible is easier to use in hands, easier on muscles & joints. Rigid is not as life like,
harder to pick up.*” Informal observations suggest participants rotated the displays as they were
moving between targets, as this allowed them to use more efficient wrist action over arm
movements. Flexibility supported this rotation better by conforming to the shape of the hand
during wrist rotation.

We found no significant effect of *Flexibility* or *Mass* on error rates. Results for the paper
condition hint that there may be an optimal level of *Flexibility* and/or *Mass*. The paper condition
appeared to perform more poorly than the flexible display condition, despite being both lower
mass and more flexible. Informal observations suggest this may be due to the paper sheets
bending more readily while moving, leading to an increase in air resistance, thus making it more
difficult for participants to hit targets at speed.
While the fit of the regression models can be considered as good, it is lower than what is normally found in pointing device experiments, including area cursor experiments [32, 48]. We believe this was due to the large size of the devices in all conditions, making it more difficult to follow a model of unrestrained hand movement. Zhai et al. [93] also note that the adjustments to the target width ($W$) resulting in use of the effective target width ($W_e$) for calculations can lower the correlation between $MT$ and $ID$.

6.6 Study 2: Throughput of Pointing Within Displays

In our second Fitts’ Law experiment, we evaluated the $IP$ of within-display interactions: pointing with one display between targets within another display. In this task, participants were asked to tap between two targets shown on one display using the top left corner of a second display that

Figure 34. Within-display tasks: A flexible low mass display pointing at a 10mm target. Tip of the display has a red cursor and reflective markers (inset).
was held in the hand. We again compared the effects of display *Mass* and *Flexibility* on performance in this task.

**H3.** We hypothesized that the Index of Performance would be higher with displays that are *Flexible* (**H3.1**), and with displays of a lower *Mass* (**H3.2**).

Pointing with displays is not a familiar or common action performed by users with existing electronic devices. A printed red cursor (Figure 34, inset) was attached to the top-left corner of each display to visually highlight the cursor location.

### 6.6.1 Procedure

Participants performed a 1D reciprocal Fitts’ Law tapping task, pointing with the top left corner of the display device between two targets of varying width and amplitude shown on the second display device. The pointing display was held in the dominant hand, while an active flexible display, taped flat on the desk, displayed the targets (see Figure 34). Participants were asked to iteratively point between two targets on the display as fast and accurately as possible. This was repeated 16 times, with the first hit recorded only for end point data, recording data points for 15 taps. A hit was recorded when the pointing display or a part of it was touching the taped display such that the tip of the printed red cursor was within the target area for at least 50 ms. An error occurred when users tapped outside the target, or did not stay in the target for at least 50 ms, in which case participants were alerted with an auditory beep.

### 6.6.2 Measurements

We collected the same measurements as in the first experiment (*MT*, *EP*, Error rate).
6.6.3 Participants
10 paid volunteers (6 females, 4 males) participated in this study. The participants were between the ages of 19 and 45 (mean 25.6 years). All of them were right-handed and performed the experiment with their dominant hand.

6.6.4 Experimental Design
We used a within-subjects repeated measures design with 2 fully factorial independent variables: Flexibility (2 levels) and Mass (2 levels) of displays. We used 3 target amplitudes (10, 100, 208 mm) fully crossed with 3 target widths (4, 7, 10 mm) resulting in 9 unique Indices of Difficulty (1.00, 1.28, 1.81, 3.46, 3.93, 4.45, 4.70, 4.94, 5.73).
Participants repeated 15 trials of each A-W pair. The order of the 9 A-W pairs was randomized for each display, and the order of the display conditions was counterbalanced.

6.6.5 Apparatus
We used the same 4 display devices from the first experiment (flexible display 83g, rigid display 83g, flexible tablet 661g, rigid tablet 661g). We did not perform a paper condition in this experiment. Our measurement apparatus was also similar. However, we used three 10mm diameter flat circular IR reflective markers precisely placed on the top-left corner of the pointing displays to track the tip of the printed cursor in 3D (Figure 34, inset). A Vicon motion capture system reported the position of the cursor's tip with an accuracy of approximately 0.2 mm. The position of the stationary display and the displayed targets were recorded prior to the start of the experiment for calibration purposes. This process accounted for the varying thickness of different display conditions.
Table 4. Fitts’ Law Experiment 2 (Within-display Pointing): Mean Effective Index of Performance (in \textit{bits/s}) and standard error (s.e.) between conditions.

<table>
<thead>
<tr>
<th>Device</th>
<th>Flexible Low Mass</th>
<th>Rigid Low Mass</th>
<th>Flexible High Mass</th>
<th>Rigid High Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$IP$ (s.e.)</td>
<td>5.90 (.56)</td>
<td>4.99 (.52)</td>
<td>5.28 (.55)</td>
<td>4.89 (.56)</td>
</tr>
<tr>
<td>Error</td>
<td>2.89%</td>
<td>2.07%</td>
<td>3.41%</td>
<td>3.41%</td>
</tr>
<tr>
<td>Model</td>
<td>-59.21 + 215.92*ID ($r^2= .85$)</td>
<td>45.18 + 227.69*ID ($r^2= .81$)</td>
<td>23.25 + 214.51*ID ($r^2= .87$)</td>
<td>56.42 + 231.54*ID ($r^2= .80$)</td>
</tr>
</tbody>
</table>

6.7 Study 2: Results

Table 4 shows the $IP_e$ values, error rates and regression model for all display types. The $IP_e$ for the Flexible low Mass condition was 5.90 \textit{bits/s} (s.e. = .56). $IP_e$ for the Rigid low Mass condition was 4.99 \textit{bits/s} (s.e. = .52). $IP_e$ for the Flexible high Mass condition was 5.28 \textit{bits/s} (s.e. = .55). $IP_e$ for the Rigid high Mass condition was 4.89 \textit{bits/s} (s.e. = .56).

A two-way ANOVA on the $IP$ scores showed a significant effect of Flexibility on device IP ($F_{1,9} = 17.02$, $p=.003$) for this pointing task, with flexible devices obtaining a higher performance. No significant effect was found of Mass on IP ($F_{1,9} = 1.82$, $p=.210$). There was no significant interaction effect between Flexibility and Mass ($F_{1,9} = 2.61$, $p=.140$). The regression model for each device is visualized in Figure 35. The fit of the model was good with $r^2 > .80$ for all display conditions.
Figure 35. Fitts’ Law Experiment 2 (Within-display Pointing): Fitts’ Law Regression for each device showing movement time ($MT$, in $ms$) and effective index of difficulty ($ID_e$, in $bits$).
6.7.1 Error Rates

Error rates were less than 4% for all devices. A two-way ANOVA showed a significant effect of Mass ($F_{1,9} = 6.50, p=.031$) on the error rates for the pointing task, with high Mass devices obtaining a higher error rate. Flexibility had no significant effect ($F_{1,9} = 1.35, p=.276$) on error rates. There was no significant interaction effect between the two factors on error rate ($F_{1,9} = 1.17, p=.307$).

6.8 Study 2: Discussion

Results confirm our hypothesis H3.1 that flexible displays perform better than rigid displays for more refined pointing tasks within displays. However, we found no significant effect of mass on the performance of the display types (H3.2). Mass did have a significant effect on the error rates.
Results suggest that a higher mass negatively affected the precision of pointing. The excellent performance of flexible displays in this task may, in part, be attributed to the use of structural holds [20]. These temporary rigid structures (Figure 36) may ease device handling and target selection while still allowing the display to give way when the hand touches down. Observations seem to confirm this behavior for most participants.

6.9 Study 3: Throughput of Dragging Within Displays

Results from study 2 showed that flexible displays were more suitable than their rigid counterparts for pointing within displays. Our final study set out to answer if we could generalize these results to other kinds of pointing, such as dragging an object with the tip of one display onto a target on another display.

**H4.** As with our two previous Fitts’ Law experiments, we hypothesized that in within-display dragging tasks, $IP$ would be higher with displays that are *Flexible* (H4.1) and having lower *Mass* (H4.2).

6.9.1 Procedure

Participants performed a standard 1D Fitts’ Law dragging task that was slightly more complicated than the pointing task [61]. Here, the top-left corner of the display, held in the dominant hand, was used to select a target (visualized as a rectangular black bar) on the second display, which was taped to a desk. After visualizing a target bar on the second display, participants tapped and held the first display on this target bar. The target bar was subsequently removed, and a new target bar was drawn at a certain amplitude on the other side of the second display. Participants were then asked to drag the first display across the surface of the second display to within this
new target bar, at which time that target bar was removed. Participants would then lift the first display to release the dragging operation [61], after which the next target bar appeared at the previously released target bar position. This task was alternated reciprocally between left and right targets on the second display. Participants were instructed to repeat the dragging operation 15 times successfully. A successful drag operation was recorded when the first display was lifted from the table such that the red cursor was within the target bar. An error occurred when users released the drag operation (i.e., lifted the display) outside the target bar, and was signaled with an auditory beep.

6.9.2 Measurements

*MT*, *EP* and error rates were recorded for the dragging operation. *MT* was defined as the time between selecting the first target and successfully lifting the display 2 mm off the second target bar. Tracking was calibrated to account for varying thicknesses of different display types. Error rates were counted but removed from analysis.

6.9.3 Participants

10 paid volunteers (6 females, 4 males) participated in the study. The participants were between the ages of 19 and 45 (mean 25.5 years). All of them were right-handed and performed the experiment with their dominant hand.

6.9.4 Experiment Design

The experiment factors and number of trials for the dragging task were the same as for the within-display pointing task, using the same display conditions (low *Mass*—Flexible and *Rigid*—displays 83g, high *Mass*—Flexible and *Rigid*—displays 661g).
Table 5. Fitts’ Law Experiment 3 (Within-display Dragging): Mean Index of Performance (in bits/s) and standard error (s.e.) between conditions.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Flexible Low Mass</th>
<th>Rigid Low Mass</th>
<th>Flexible High Mass</th>
<th>Rigid High Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP (s.e.)</td>
<td>2.61 (.09)</td>
<td>2.69 (.11)</td>
<td>2.37 (.13)</td>
<td>2.48 (.18)</td>
</tr>
<tr>
<td>Error</td>
<td>3.33%</td>
<td>2.59%</td>
<td>3.41%</td>
<td>4.00%</td>
</tr>
<tr>
<td>Model</td>
<td>559.54 + 223.60*ID (r²=.79)</td>
<td>548.72 + 214.61*ID (r²=.87)</td>
<td>556.39 + 276.70*ID (r²=.65)</td>
<td>627.46 + 244.25*ID (r²=.63)</td>
</tr>
</tbody>
</table>

Figure 37. Fitts’ Law Experiment 3 (Within-display Dragging): Fitts’ Law regression for each device comparing movement time (MT, in ms) with effective index of difficulty (IDₑ, in bits).
6.10 Study 3: Results

The IP values, error rates and the regression model for each device are summarized in Table 5. The IPe for Flexible low Mass condition was 2.61 bits/s (s.e. = .09). IPe for Rigid low Mass condition was 2.69 bits/s (s.e. = .11). IPe for Flexible high Mass condition was 2.37 bits/s (s.e. = .13). IPe for Rigid high Mass condition was 2.48 bits/s (s.e. = .18). A two-way repeated measures ANOVA on the IP scores of 4 conditions separated by 2 factors showed a significant effect of Mass on display device IP (F1,9 = 6.78, p=.029) for dragging, with low mass devices obtaining a higher performance. No significant effect was found of Rigidity on IP (F1,9 = 2.22, p=.170). There was no significant interaction effect between Rigidity and Mass (F1,9 = .05, p=.824). Figure 37 shows the regression model for all devices.

6.10.1 Error Rates

Error rates were within 4% for all devices. A two-way ANOVA showed a significant interaction effect between Flexibility and Mass (F1,9 = 5.65, p=.041) on the error rates for the dragging task. No significant effect was found for Flexibility (F1,9 = .02, p=.891) and Mass (F1,9 = 3.60, p=.090) on error rates.

6.11 Study 3: Discussion

Results showed no significant effect of Flexibility on the IP for dragging tasks in within-display dragging tasks (H4.1). However, there was a significant effect of Mass on the IP in this task (H4.2). This suggests that display devices with a lower mass are more suitable for dragging operations. Prior research [61] has shown that dragging is a more challenging task, as it requires more muscle tension than pointing for the same task conditions. While MacKenzie et. al. [61] report lower IPs for dragging versus pointing for mouse, tablet and trackball, they also report a
very high error rate for dragging. Our results, while remaining within the 4% error rate, shows significantly low $IP$ values and high intercept values (> 400 ms) for all display types.

During the dragging tasks, we observed the participants pausing on the second target prior to lifting the device (to record a successful drop operation). We might attribute this to significantly higher muscle tension involved in handling large 10.7” displays, both in sustained dragging and lifting operations. We compared movement times for the smaller targets and larger targets to assess the effect of small target sizes on the intercept values, but found no evidence to suggest that participants were more careful when aiming for smaller targets.

We conclude that large devices are not suitable for precise dragging operation within displays. Further user studies that compare the effect of input device size on dragging tasks may be warranted.

6.12 Summary Discussion
We reported on three Fitts’ Law experiments that compared the $IP$ of displays of varying flexibility and mass for Between-display and Within-display interactions. Results suggest that, when moving displays around on a desk, low mass flexible displays provide an increase in the Index of Performance of 8.4% over rigid displays of the same mass. $IP$ was 15% higher for low mass flexible displays than flexible tablets of high mass, and 30% higher than rigid high mass tablets. Informal observations suggest that flexible displays supported movement by conforming to the shape of the hand during wrist rotation while targeting, reducing strain and fatigue.

Results from pointing and dragging within-displays complement each other. For within-display pointing tasks, where users pointed with the tip of one display onto another display, low mass flexible displays improved the Index of Performance 18% over rigid displays of the same mass. Performance was 12% higher for flexible displays of low mass than for flexible displays of
high mass, and 21% higher than for a rigid high mass tablet. Mass negatively affected error rates when pointing.

It appears that flexibility is an important performance factor in pointing within displays, but not for dragging. We believe this is because the display stayed on the target surface during dragging operations. In dragging tasks, low-mass displays, however, did perform better than high-mass displays, irrespective of rigidity. Unsurprisingly, the low $IP$ for dragging tasks suggests that large sized displays are not suitable for this task. Overall, results indicate flexible, low mass displays are better suited for multi-display environments than traditional tablet PCs.

6.13 Limitations and Directions

While we studied, and compared a variety of tasks with different devices in a multi-display context, these were confined to 1D Fitts’ law experiments. This was a first step, and these experiments can be extended to 2D and 3D target acquisition tasks. Comparison of flexible displays with paper hint that there might be an optimal level of mass and/or flexibility desirable for multi-display interactions. Adding more levels to these two factors might provide insights. Finally, we note that in terms of technology, we compared an idealized flexible device with off-loaded rigid electronics with an existing commercial device that included all electronics. However, it is reasonable to expect that flexible circuits, chip and battery technologies will contribute to the realization of flexible, lightweight paper computers within the next decade.

6.14 What is a Paper Computer?

Results of our Fitts’ law studies answer the key question of the need for thinness and low mass in spatial interactions with large displays. We formalize our definition of paper computers based on these results and three key factors: literature exploring the usage of paper in everyday knowledge
work; our experience with designing and developing DisplayStacks and PaperTab systems; and qualitative user feedback.

We define a Paper Computer as an interactive system consisting of multiple physical ‘tabs’ supporting spatial interaction with digital information. In addition, a paper computer has the following properties:

**Self-contained**: Each tab is completely untethered during interactions. Each tab also encapsulates display, sensing, processing, communication, and power in a paper-like thin and lightweight form factor.

**Self-aware**: Each tab is aware of its own deformations, i.e., sensing bends, shape changes, and actuations.

**Interconnected**: Each tab is able to communicate with other tabs. In addition, they track the relative and/or absolute position of all tabs in the system.

**Adaptive**: Tabs can be added or removed from the system at any time. The system functionality fluidly adapts to varying number of tabs.

DisplayStacks and PaperTab prototypes are far from being ideal paper computers. However, our experience with designing and developing these systems allowed us to reflect on the importance of the different properties of paper computers.

### 6.15 Summary

In this chapter, we evaluated core interaction techniques for multi-display electronic paper computers. We reported on three Fitts’ Law experiments that compared how display flexibility and mass affect the efficiency of Between-display and Within-display pointing tasks. Results strongly suggest that both flexibility and low mass of the display have a significant positive effect
on performance in Between-display pointing tasks. However, displays that are too flexible may negatively affect pointing performance due to random shape changes that occur during movement of the display. We also found a positive effect of flexibility on performance when pointing with one display at targets within a second display. Mass only affected the error rates in this task. Large displays are typically not suited for dragging operations. A strong negative effect on performance was observed for display mass during dragging operations.

We conclude that multi-display paper computers benefit from the use of flexible, lightweight displays. Tablet PC form factors do not form a proper substitute for flexible displays when building multi-display, paper-like user interfaces. With this assertion, we define paper computers as multi-display systems with specific properties supporting spatial interaction with digital information.
Chapter 7

Conclusion and Future Work

7.1 Summary

Physical paper provides key physical attributes and spatial cues that enable superior handling of information on a desk [77]. Modern computers and GUIs, despite their speed and scalability, do not fully exploit the haptic, bimanual and spatial attributes of physical documents.

In this thesis, we set out merge the benefits of physical paper with that of computers by building multi-display paper computers using high-fidelity flexible displays. We progressed from developing single-display deformation interactions (Snaplet), to multi-display stacking interactions, in a mobile form factor (DisplayStacks, ) onto multi-display spatial interactions in large paper-sized form factor (PaperTab, ). Each of our prototypes exploited the unique physical properties of flexible displays to support paper-like interactions. Despite the inherent limitations in the underlying hardware we were able to qualitatively and quantitatively evaluate paper computers and established the usefulness and importance of using thin-film displays in paper computers. We formalized the definition of paper computers.

With Snaplet, we exploited the flexibility of thin-film displays to design a deformable computer. With DisplayStacks, we explored stacking interactions with digital media, made possible by the thinness of flexible displays. We explored spatial interactions with PaperTab, requiring large low mass displays.

We built a myriad of prototypes and learnt the challenges of building thin-film interfaces and their underlying sensors.
Our quantitative studies asserted our fundamental assumption that we need thin and low mass displays for paper computers.

7.2 Contributions

We revisit the contributions stated in the beginning of this thesis and summarize our work.

Contribution 1: We used flexible displays to build high-fidelity, multi-display, paper computer prototypes for deployment and evaluation of paper-like interactions.

We followed an iterative design approach to design and develop three flexible display prototypes. In addition to realizing our proposed interaction techniques, we set distinct goals when developing each of our prototypes. Snaplet used 3.7” Bloodhound flexible electrophoretic display to explore deformation as input. With this prototype, we tested the feasibility of interfacing with flexible displays and sensing different inputs in a thin-film form factor. These lessons formed the foundation for building our multi-display prototypes.

DisplayStacks explored stacking interactions with digital information using multiple Bloodhound displays. With the DisplayStacks prototype, building our first fully functioning paper computer was the primary goal. To this end, we did not formally evaluate this system. We designed a custom sensor layer for tracking displays in a stack. In addition, we provided pen and bend input for each display. We encountered some challenges of spatial sensing in a thin-film form factor.

PaperTab represented the culmination of our efforts in building a paper computer. Robustness and support for user evaluation of paper computers were the primary goals for the PaperTab prototype. We explored three different iterations of the prototype and were successfully
able to use large 10.7” displays to build and evaluate our proposed interaction techniques. With each of the three prototype versions, we deliberated upon different ways of designing the software and the hardware architecture of paper computers. We used off-the-shelf sensors to support spatial tracking and touch input. In addition, we customized the PaperTab prototype to quantitatively evaluate the efficiency of moving physical displays on a desk.

All of our displays suffered from limited mobility due to each display being tethered to rigid electronics via ribbon cables. This did not affect the deployment and evaluation of interaction techniques. However, it did impact scalability, i.e., adding more displays in each prototype.

**Contribution 2:** We designed spatial and bimanual interaction techniques taking advantage of the affordances of flexible displays.

Paper-like interaction with digital information has been explored with GUIs [2,47,63], tabletop interfaces [50,80,81], and tablet-based interfaces [13–15]. However, flexible displays mimic three unique physical affordances of paper: thinness, low mass, and flexibility. While flexibility was not our primary focus, we explored how these affordances supported paper-like interactions with digital media.

Snaplet exploited the flexibility of these displays for deformation based interactions. Low mass was beneficial for the wearable scenario we explored with Snaplet. Change in display shape was triggered by its relation to users’ body. This in turn triggered change in its functionality.

DisplayStacks focused on the key attribute of thinness of flexible displays to explore stacking as a form of organizing and interacting with digital media. Low mass was beneficial for
mobile interactions, while flexibility was used for providing bending as an alternate form of input. We presented 8 unique display configurations achievable by a stack of displays. In addition, we supported context-based interactions with partially occluded displays in a stack.

PaperTab explored spatiality of tabs, for interacting with digital media, made possible by the low mass of the displays. PaperTab also supported stacking and bend interactions, taking advantage of thinness and flexibility. We introduced two categories of interaction techniques for PaperTab: Between-display and Within-display interactions. Between-display interactions encompass spatial and proximity-based interactions with displays on a desk. Within-display interactions introduce the concept of selecting and interacting with information within a display by using the tip of another display.

With our paper computer prototypes, we merged the physical affordances of paper with the speed and scalability of computers.

**Contribution 3:** We evaluated different display types and demonstrated that electronic paper computing environments benefit from the use of flexible displays.

A qualitative evaluation of PaperTab indicated that users found PaperTab and its associated interaction techniques easy to learn, without inducing significant physical demands or mental demands. However, due to the prototypes being tethered, we were unable to deploy a long-term study to understand the benefits and challenges of our prototype.

A key question was left unanswered in prior work exploring paper computers: Do paper computers need flexible displays? We investigated how mass and flexibility relate to throughput of movement with displays as area cursors. We reported on three Fitts’ Law experiments that
compared how display flexibility and mass affect the efficiency of Between-display and Within-display pointing tasks.

Results strongly suggest that both flexibility and low mass of the display have a significant positive effect on performance in Between-display pointing tasks, i.e., hypotheses H1 and H2 were validated. However, displays that are too flexible may negatively affect pointing performance due to random shape changes that occur during movement of the display. We also found a positive effect of flexibility on performance when pointing with one display at targets within a second display, validating H3.1. Mass only affected the error rates in this task. H3.2 was invalidated. Large displays are typically not suited for dragging operations. Both H4.1 and H4.2 were invalidated. A strong negative effect on performance was observed for display mass during dragging operations.

**Minor Contributions**

We reflected on prior art and our own prototypes to formally define paper computers. We outlined key factors that are essential to categorize an interactive system as a multi-display paper computer. Additionally, we built multiple iterations of the DisplayStacks and PaperTab prototypes and discussed different ways of designing software and hardware architectures for multi-display paper computers.

**7.3 Future Work**

**7.3.1 Untethered displays**

The biggest limitation of our paper computers is the tethered nature of our displays. This reflects the current state-of-the-art in processor technology and battery electronics—they continue to be
rigid. Advances in organic electronics, nanotechnology, and battery technology make us hopeful of working with untethered displays that retain their thinness, flexibility, and low mass.

The reflective properties of electrophoretic ink displays make them ideal for deployment in paper computers. However, the low refresh rate and lack of availability of full gamut of display colors limit the capabilities of rich multimedia experiences that we can explore. We believe that the emerging technology of FOLED (flexible organic light emitting diode) displays will overcome these limitations.

Lastly, we hope to incorporate portable and lightweight spatial tracking technologies into our displays to take the final leap of a fully wireless and interactive paper computer. Lightweight vision-based tracking technologies [100] and ongoing efforts in indoor GPS technologies show promise.

### 7.3.2 Long-term Evaluation

Aliakseyeu et al. [4] observed that speed and performance of interaction techniques are not always sufficient. They concluded that engagement and effort needed to be used for evaluating (in their case, piling) interaction techniques. We propose to run long-term user studies with robust and untethered version of PaperTab. While the current user feedback and the quantitative study results have been positive, a longitudinal study would allow us to understand how users adopt paper computers into their everyday lives. These studies may provide further insights into the opportunities for paper computers in different work settings, such as offices and universities, as well as for supporting different workflows. Rigid electronics and limitations of current battery technology continue to be the key barriers for deploying longitudinal studies.
7.3.3 Designing for Appropriation

The resilience of paper comes from its ability to adapt to different settings and workflows. We believe that this repurposing of paper by its users is a key factor that determines the usefulness and usability of paper computers in the long run. While we incorporated well-observed paper-usage strategies in our interactions, we acknowledge the limitations of our current prototype in adapting to users' needs. This was reflected in the feedback of PaperTab’s qualitative study. Users wanted to be able to change the meaning and location of zones; they wanted to reassign bend gestures to better fit differing mental models; and they wanted to be able to assign different corners of tabs to support different pointing actions. We hope to rethink interactions, hardware, and software of paper computers, with a focus on supporting end-user appropriation [21].

7.3.4 Different paradigms of interacting with Paper Computers

Our current set of paper computer prototypes and associated interaction techniques focused on pursuing a narrow opportunity for designing paper-like interfaces and interactions. We took advantage of thinness, low mass, and flexibility of displays to build bimanual and spatial interactions, much like paper.

However, research in paper computers can greatly benefit from adopting other existing avenues of human-computer interaction: tabletop computing, computer-supported collaborative work, and pen-based interactions.

Looking towards the future, we can explore the use of self-actuating displays [27], haptic feedback in displays [82], and self-reconfiguring displays [30], to name a few, to enhance the way we interact with digital media.
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Appendix A

Building Flexible Circuits

Figure 38. Interactive Origami Boat made with custom-designed flexible copper circuit.

Flexible circuits have been used commercially for the past forty years. Their ability to conform to different shapes (for example, wrapped around a rigid battery), while being lightweight, make them ideal for manufacturing smaller, thinner, and lighter electronic devices. Additionally, flex sensors, force sensitive resistors, potentiometers, and even touch sensors are commercially available in a thin-film form factor.

We designed a method for building low-cost flexible circuits with a quick turnaround time. The method is an improvement over existing methods of etching copper circuits [101]. We conducted a workshop on building flexible circuits [85]. As a part of this workshop we built an
interactive origami boat (see Figure 38) to demonstrate the potential of flexible circuits to the participants. The boat was made entirely out of a sheet of copper. The copper sheet had circuit etchings and LEDs soldered onto the surface. Picking up the boat by grabbing its sail completed the circuit and lit up the LEDs. We use this example to illustrate and describe the steps for building a flexible circuit.

**Step 1** We use Dupont Pyralux copper-coated polyamide sheets to build our flexible circuits. We measure and cut 216mm x 279mm (i.e. Letter size) Pyralux sheets (Figure 39.a). The copper surface is cleaned using rubbing alcohol.

**Step 2** We use Eagle CAD software or any vector editor software to design our circuit for etching (Figure 39.b). It is essential to make sure that the design consists of only black and white colours. Note that the white colours correspond to the copper that will be etched away by chemical reaction leaving behind the flexible polyamide layer. Figure 39.b shows a large portion of the circuit in black. This ensures that the circuit etching process takes less time as the unneeded black regions can be cut away from the final circuit.

**Step 3** We need to transfer circuit design onto copper to form etch resist. An etch resist is a layer of material deposited on top of those regions copper sheet that we do not want to be removed through chemical etching process (i.e. black regions in our circuit design.) We use a solid ink printer to transfer our circuit design onto the copper sheet. A layer of wax ink gets coated on the
copper surface (Figure 39.c). Special toner transfer papers can also be to complete this process with regular inkjet printers.

**Step 4** Etching process: We use 10% hydrochloric acid (HCL) with water to create the etching solution. The ratio of mixing the two ingredients is typically 1:1. However, more HCL can be added for faster etching. The printed Pyralux sheet is completely submerged in the solution (Figure 39.d).

**Step 5** The etching process typically takes 15 to 30 minutes depending on the amount of copper to be etched (Figure 39.e). Once the process is complete, the etched circuit is exposed by wiping the surface with acetone and removing the etch resist layer (Figure 39.f). Once the sheet is completely clean and dry (Figure 39.g,) it is ready for use.

**Step 6** The etched sheets and thin and flexible enough to be folded. We can now solder different electronic components onto these copper circuits (Figure 39.h) similar to any rigid copper circuit board. However, due to the sheet's flexibility, there are larger chances of electrical connections of the soldered components to get affected by constant bending. These issues can be overcome by using commercial printing services for more resilient flexible circuits.
Figure 39. Steps for designing and building custom flexible circuits.
Appendix B

Research Proposal Approval Letter

August 25, 2014

Dr. Roel Vertegaal
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Goodwin Hall
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GREB Romeo #: 6006189
Title: "GCISC-052-11 PaperDesk"

Dear Dr. Vertegaal:

The General Research Ethics Board (GREB) has reviewed and approved your request for renewal of ethics clearance for the above-named study. This renewal is valid for one year from August 23, 2014. Prior to the next renewal date you will be sent a reminder memo and the link to ROMEO to renew for another year.

You are reminded of your obligation to advise the GREB of any adverse event(s) that occur during this one year period. An adverse event includes, but is not limited to, a complaint, a change or unexpected event that alters the level of risk for the researcher or participants or situation that requires a substantial change in approach to a participant(s). You are also advised that all adverse events must be reported to the GREB within 48 hours. Report to GREB through either ROMEO Event Report or Adverse Event Report Form at http://www.queensu.ca/ors/researchethics/GeneralREB/forms.html.

You are also reminded that all changes that might affect human participants must be cleared by the GREB. For example you must report changes in study procedures or implementation of new aspects into the study procedures. Your request for protocol changes will be forwarded to the appropriate GREB reviewers and/or the GREB Chair. Please report changes to GREB through either ROMEO Event Reports or the Ethics Change Form at http://www.queensu.ca/ors/researchethics/GeneralREB/forms.html.

On behalf of the General Research Ethics Board, I wish you continued success in your research.

Yours sincerely,

Joan Stevenson, Ph.D.
Chair
General Research Ethics Board

c.: Mr. Aneesh Tarun, Co-Principal Investigator
    Mr. Paul Strohmeier, Co-investigator
    Ms. Karilee Reinbold, Research Coordinator