ペーパーライク・コンピューティング

Paper-Like Computing

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要　旨

電子機器とのユーザインタラクションを紙により近づける重要な取り組みを紹介する．紙を用いた従来の業務ワークフローに可能な限り近づけつつ，電子機器の利点をもたらすという特徴を持つシステムを導入して，「ペーパーライクコンピューティング」と定義する．中でも，フォーム処理の業務ワークフローに着目する．ここでは，ペーパーライクコンピューティングデバイスの重要要件を特定して，ペーパーライクディスプレイと紙との類似点，本デバイスがもつ共通の課題の解決手段を述べる．さらに携帯性，使いやすいインターフェース，コンテンツの共有しやすさなどを含むユーザニーズを特定する．我々は，上記要件を考慮しながらデバイスを設計し，合計21台のユニットを組み立てた．これらのユニットを用いて，ディスプレイサイズ，ペントラッキング（追跡）の待ち時間および業務ワークフロー全体における本デバイスの有効性を評価した．この結果，ペントラッキングは成功し，本デバイスのディスプレイサイズはフォームの表示に十分であること，フォーム上のタスク遂行に本デバイスが有効であることを確認した．さらに，ペーパーライクコンピューティングデバイスを設計するに当たり，電力管理，触感がフィードバックされるユーザインタフェースボタン，デバイス全体としてのサイズ・重量が重要な設計基準となることも確認した．本デバイスは，バックエンドシステムとのユーザインタラクションを改良することができ，フォーム処理の業務ワークフローに有効に使えるデバイスであると言える．

ABSTRACT

We discuss significant challenges in making user interactions with electronic devices more paper-like. We define paper-like computing as the introduction of a system that brings the advantages of electronic devices into business workflows that is as similar to working with paper as possible. Our particular focus is on forms processing workflows. We identify key requirements for a paper-like computing device, and describe how paper-like displays are similar to paper, together with how to overcome common issues of paper-like displays. We identify additional user needs, including portability, a familiar interface, and easily shared content.With these requirements in mind, we designed a device, and built twenty-one units. We used these units to evaluate the display size, pen tracking latency, and its overall usefulness in workflows. Our results indicate the display size was sufficient for the forms we used, the pen tracking was successful, and the devices were useful for their tasks. We also discovered that power management, tactile user interface buttons, and overall size/weight are important design criteria for paper-like devices. Although users still preferred paper over the device, the improved interaction with backend electronic systems make this a useful device for forms processing workflows.

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1. Introduction

The push to use less paper in the office in the interest of workflow efficiencies, and being more ecologically friendly is very real these days. Employers encourage printing less and using more recycled paper. However, business workflows are still largely paper-based. According to a recent study by Xerox and Harris Interactive, 37% of business respondents agree that their organizations are drowning in paper and 50% feel that their organization's business processes are paper-based. [20] There are many good reasons why paper-based workflows are still so prevalent, including familiarity, flexibility, and robustness.

One way to reduce paper use is to convert business workflows, like timecards, expense reports, and purchase requests, to electronic forms. The advantages of moving to an electronic workflow are enormous, but the costs of implementing it are staggering. Consider the medical industry. According to Karen Bell, Director of the U.S. Office of Health IT Adoption:

> "...despite the benefits, only 15 to 18 percent of U.S. physicians have adopted electronic health records. ... Physicians have to shell out considerable upfront costs and lose about 20 percent productivity in the first few months as personnel get used to the system." [1]

It is appealing to find new ways for businesses to convert to electronic workflows, without incurring large up-front IT and training costs, and without sacrificing the user experience. This motivated us to experiment with "Paper-Like Computing" — i.e., with electronic systems characterized by their similarity to the experience of working with paper. We have developed a hardware and software platform to allow us to experiment with paper-like workflow systems, comprising a thin, low-power device with a paper-like display and a pen input. We've developed technology for fast pen tracking and improving contrast to make the device behave like a clipboard with paper forms. Designing a device intended to be similar to paper is very different from designing a device intended only for reading.

2. What is Paper-Like Computing?

The dream of paper-like computing is the introduction of a hardware/software system that is so similar to paper, that it seamlessly blends all the advantages of electronic devices into business workflows in such a way that users hardly notice they're not using paper anymore.

Workflows in a business environment still rely partially, if not fully, on paper at some point in the process. But transitioning workflows across electronic/paper domains is a lossy process — for example, any time an electronic document is printed and scanned back later, the scanned document is only an image of the original form, and is not as useful as the original electronic document. Paper-like devices may replace many workflow steps by an electronic device, keeping documents in their original formats. The electronic device augments the workflow with new capabilities (error-checking, etc.). Ideally, the electronic device is so similar to paper that it "just works" in the existing workflow. This means that forms do not have to be re-designed, they are simply scanned onto the electronic device and used as-is. System installation is almost as easy as replacing clipboards with portable devices, and it requires little re-training, and can co-exist with legacy paper-based workflows.

There are several research and commercial devices that place paper-like system intelligence in the pen, and function on regular paper [25), 17), 13)]. We use a more standard shaped pen, and place the computer in the paper, which allows strokes to be generated and erased, pages to be updated, and displays multiple pages. Meanwhile, we maintain a paper-like interface, not attempting to display cursors, windows, or menus.

After identifying system requirements from user needs for paper-like computing, we found that no current device meets the needs of paper-like computing. In this paper, first we discuss a key component of any device designed for paper-like computing, a paper-like display. Then the other hardware components and software that make a paper-like computing system possible are discussed. Finally, we describe our user studies based on the device we actually built.

3. About Paper-Like Displays

If a device is intended to emulate paper, the expectations of the user must be met with the characteristics of the device's display. User needs, and how electronic paper displays meet these needs, especially when compared with more traditional displays, such as LCDs (liquid crystal displays), are discussed below.

Paper is Portable

Anyone who wants to use an electronic device as if it were paper is not likely to tolerate a device tethered to a wall. Paper is highly portable, so any paper-like device must be portable, too. Electronic paper displays consume zero power except when changing the page. In fact, battery-life for most of the devices based on electronic paper is often specified in terms of page-turns, rather than hours. [22] In a portable device, longer battery life is key, and paper-like displays are best positioned to meet this need.

Paper is Easier on the Eyes

Research has shown that human eyes fatigue faster when reading on a traditional LCD display than paper, or an electronic paper display. Inoue, Sakamoto, and Omodani claim that:

"These results suggest that the electronic paper used in this study (Sony Libre) is superior to conventional displays (LCD) with regard to avoiding fatigue in reading tasks. ... The free handling of the medium enabled by electronic paper should be regarded as contributing to the reduction in eye fatigue." [11]

Electronic paper displays are not as tiring on the eyes as traditional displays.

Paper is Easy to Read Outdoors and Indoors

The display quality of a standard LCD is "washed out" by the ambient sunshine. The displays become difficult to read. Electronic paper displays are a reflective light technology — that is, the light users see on electronic paper displays is ambient light reflected off the display itself. This is identical to how users interact with paper. Conversely, in low ambient light, electronic paper displays, like real paper, are difficult to read.

Paper-Like Displays are not Perfect

Clearly, electronic paper displays emulate the real thing — paper — much more effectively than traditional displays. However, with these benefits also come several drawbacks. These will be discussed below. It is beyond the scope of this paper to delve into the details as to the physics of the electronic paper displays, and hence the causes of these issues, but many papers, especially from E-Ink, reference these issues. [26]

Low Pixel Update Rates. Vizplex, E-Ink's latest generation electronic paper display film, requires 260msec to update in 1-bit mode, and as long as 740msec in grayscale mode. [4] While users expect to turn pages of a book in sub-seconds, or even more challenging, quickly flip through many pages of a book looking for a particular chapter or picture, this type of interaction is very difficult to emulate on an electronic paper display. Pixels simply do not move change enough to display all that information.

Image Ghosting. Image ghosting is another issue with electronic paper. Due to the physics of E-Ink displays in particular, image ghosting occurs when updating the image from image-A to image-B. Faint ghost lines of image-A will remain in the background of image-B, reducing the clarity and contrast of image-B. Figure 1 shows a simulated example where image-A is a black "E" and image-B is a black "I". In a forms workflow, where a device is re-used from one customer to the next, ghosting may actually leave a shadow of prior answers on the form. This is not desirable if the form is in a health clinic, for example.

Fig.1 Example of image ghosting on an electronic paper display. [26]

There are solutions to the image ghosting problem. E-Ink, for example, in order to obtain the highest contrast least-ghosting images, recommends flashing all the pixels from full white to full black, and back to full white again. At a high level, this "resets" the electronic paper pixels, ultimately allowing an accurate gray level position result on the final image. However, when driving the pixels full white to full black, at the update rate of 260msec per update, this appears as if the entire display is flashing, which is disturbing or annoying.

Color. All available electronic paper displays available today are monochrome, except the Fujitsu FLEPia. Currently, 16 gray levels is the greatest number of pixel shading variations available in these types of displays. [4] Some companies have added color filters on top of existing electronic paper displays to achieve color, but this reduces resolution, as well as overall color saturation. [18] Our brief analysis of business forms shows that color is not essential for many business workflows.

4. Designing a Paper-Like Device

There is much more involved with paper-like computer than just using a paper-like display. There are other attributes of paper that must be emulated as effectively as possible by the device in order for it to be more paper-like. Some of the previously discussed display characteristics, such as "Paper is portable", must be applied to the whole device.

Paper is thin, and lightweight. However, technology is not available today to match the thickness and weight of single sheets of paper. Devices should compare favorably with books and clipboards, and considered to be collections of paper pages, because they can store so much information.

Paper is easy to use. It doesn't come with instructions or require initialization. This device must be as obvious and as easy to use as possible, yet flexible for a wide variety of applications.

Paper is inexpensive, and information on paper is easy to share with others. In fact, paper is so inexpensive, that one does not hesitate to just "give" a piece of paper to another person! Again, at today's costs, electronic devices are not likely to approach the cost of a sheet of paper soon, but unit design decisions must be made with practical cost considerations in mind. Solutions are needed to easily share documents between electronic devices, as easy as giving a piece of paper to someone.

Paper has important and well-understood properties for security and sharing. Users have the option to make many copies for wide distribution, or make just one to share with one person. But this type of sharing in an electronic domain is not as tangible and more error-prone (e-mails are often sent to too many, or to the wrong, people). A paper-like device should implement safe secure data transfers that are as easy to use as paper.

There are many ways to capture information on paper — drawing, printing, writing, and sketching. A paper-like device must allow many forms of input as well.

Paper allows the user to draw free-form figures, and write anywhere on the page. Often, when users complete forms on electronic devices, they are constrained as computer forms, with specific fields for entry, requiring specific types of information. Specific fields often support only the automated part of a workflow. Critical parts of workflows done by humans often require users to write in the margins, draw figures, write in different sizes/colors, etc. Electronic forms must support the same flexibility.

Finally, there are substantial differences between designing an electronic device for reading purposes, and designing an electronic device to emulate paper in a business workflow. There are two key aspects to consider: (a) most paper-emulating devices today function more as readers and are not appropriate for business workflows; and (b) aspects of electronic paper devices that are not paper-like must be overcome.

Existing Devices are not Business Workflow Devices

As we do research on paper-like computing, we must consider using devices that are already commonly available. These devices will be much less expensive, and quicker to deploy for research testing. There are, in fact, a number of very popular electronic devices that have been designed to emulate paper, and to some extent, they may also be re-targeted at the business environment. A good reference for an updated listing of available devices is at Wired. [9]

While these devices are all different in how they attempt to meet their user expectations, the fundamental technologies involved are quite common. Critically, they all employ a paper-like display, as already discussed in this paper. Most use the display from E-Ink Corporation. Furthermore, they are similar to slate-tablets, thin, lightweight, with long battery life, a single active surface, and are single-page sized (although, of different sizes between vendors). However, it is interesting to note that Chen, et. al., have shown that dual-display devices offer significant advantages in document navigation, making it easier to find content as well as re-reading material. [2] In most cases, the User Interface consists of buttons or capacitive sensing. All allow cable connections to a standard PC for document synchronization and/or power recharging, and most provide some form of wireless connectivity.

However, as implied by the label of these devices, "electronic readers", most do not support writing capability. This renders them mostly useless in a business world where markup and signature requirements (i.e., filling out forms) are commonplace.

Alternatively, tablet PC's offer many alternatives for electronic workflows. A leader in this design space is MotionComputing [16]. Tablet PC's support both read and write capability in a device versatile enough to suit a wide variety of applications. But they tend to be too heavy for prolonged use (3.3 pounds for the Motion Computing example). Furthermore, they are more complicated to run and maintain, and in many cases their high price point prevents widespread proliferation.

iRex technologies developed the Digital Reader, which is an electronic paper based device that allows stylus input [12]. Similar devices are expected from other companies in the near future, although it's unclear if they will allow writing capability [18]. These devices come close to many paper-like qualities, but are much better for note-taking, than emulating paper in a business workflow. Current devices suffer from an attempt to emulate LCD displays with the user interface.

Overcoming Non-Paper-Like Aspects with Electronic Devices

As stated above, there are some characteristics about paper-like displays that must be overcome to attain paper-like computing.

Pen Tracking. Any electronic device intended to replace paper must support document markup. In their book, "The Myth Of The Paperless Office", Sellen and Harper state that [21]:

"Paper readers extensively annotated the article we gave them to summarize as they read through it. They underlined, used asterisks, and made notes in the margin."

Supporting pen-based-markup of electronic documents is critical in paper-like computing, but with a 260msec pixel update rate of electronic paper displays, it would seem that fast-pen-tracking is impossible.

Most devices with E-Ink displays do not support pen-based input, thereby avoiding this problem. As a result, these devices require more complicated user interfaces (Amazon's Kindle adds a full-function keyboard), bypassing an opportunity for user interaction in a paper-like manner.

Another option vendors have chosen in order to support pen-input on electronic ink displays is to create their own controller IC, such as iRex [10]. However, most development companies are not in a position to support such a large undertaking.

The authors of this paper instead researched the workings of an electronic ink controller, which is normally considered to not support fast pen updates. Using the controller in a novel way, we found that fast pen tracking with this existing controller is indeed possible [6]. In fact, we found that our method of fast pen tracking is faster than other known methods available, even when normalized for processor speeds and functional differences (Table 1) [8]. This speed difference has a large impact on the user, and helps the interaction with the device to be more natural, more paper-like.

Table 1 A comparison of pen tracking latencies on electronic paper displays [8].

Pen Tracking	Measured Latency (ms)
iRex	200
AM300 Broadsheet Kit	100
Author's Solution	67

Fast pen tracking (low-latency) is not only a good attribute for system design, but is also critical for a positive user paper-like experience. Miller states that[15]:

> "Where the lines are drawn with deliberation by the user — relatively slowly as compared with slashing sketch strokes — a delay of up to 0.1 second seems to be acceptable. There must not be variability perceived by the user in this delay."

The user experience decreases if the pen tracking latency grows beyond 0.1 second. However, Miller's research focused on slow and deliberate movements. Further research has shown that actual pen writing involves secondary common adjustments, for which feedback is required to be even faster. Meyer, et al., showed that these secondary adjustments occur in the 100~160msec timeframe. [14] To feel unconstrained to the user, the delays should not exceed half this time, i.e., close to 50msec.

Ghosting Reduction. We have researched several ghosting-reduction methods, including adding an intermediate display update with a pseudo-random noise display [8], and using digital halftoning on image updates to compensate for the ghosting artifacts [7]. These methods are useful to achieve the high display quality on displays that users expect with electronic (non-paper!) devices, without the annoying flashing which resets the pixels to a known state before driving the desired image.

Color. As already stated, most electronic paper displays today are monochrome grayscale, and do not support color. This aspect of paper-like computing must be considered when designing applications.

What role does color play in business workflows — it color essential? Business workflows are usually forms that get passed from one person to another, and are modified with a pen. Color on the form can help clarify or make sections more interesting, but color is not a key component of the workflow requiring the form to be completed.

While color support would indeed be an asset, we found by analysis that its lack did not hinder the results of the research performed in this report.

Selecting Components for a Paper-Like Device

There are many design options for a custom device, but we highlight the significant design decisions here.

Primary Display. We have already established the virtues, and issues, around an electronic paper display for a paper-like computing device. But there are still several design decisions to be made — which type of paper-like display to choose? Several manufacturers provide electronic paper displays based on several different technologies, but E-Ink's film is desirable in terms of quality and availability.

E-Ink panels are available in a number of different sizes, the largest being 6" (800x600) or 9.7" (1200x825). Note from Table 2 that the larger E-Ink panel has a better resolution than even the much-larger XLibris display (color, LCD), evaluated by Price, et al [19]. We found that the 6" display is just too small to display full page forms. 9.7" displays are available, but their active viewing area is only half that of a standard 8.5x11" sheet of paper. However, obtaining E-Ink panels larger than this size becomes cost-prohibitive. As a result, one of the goals of this research was to determine if the high-resolution 9.7" E-Ink display is sufficient for forms processing in a business workflow.

Table 2 A comparison of displays and resolutions.

Panel (diagonal dim)	Resolution
E-Ink 6"	800x600
E-Ink 9.7"	1200x825
XLibris 12.1"	1024x768

Another important aspect of the choice of primary display for a paper-like device is the "cost of adoption" of the device. If a new electronic device is too difficult to use, or it is too difficult to integrate into existing workflows, its use will be quite limited. More explicitly, it is vital that forms used in paper workflows do not need to be re-designed for paperless use. It takes too much time and re-training to redesign a form at many customer sites. The display needs to be large enough, and of sufficient resolution, to allow blank forms to be scanned into the electronic system, and worked on in the electronic flow, without any further modification.

Microprocessor. To save cost and design time, the authors decided to take advantage of processor modules designed by other vendors and design our system around them, rather than do a processor design from scratch. There are a large number of excellent microprocessor modules available. The authors conducted a survey of available modules, considering such features as cost, size, power, performance, technical support, software support, serial busses, and GPIOs.

Table 3 shows the functions that were most critical to our needs: processor type, power, size, GPIOs, and overall support. Ultimately, we selected the Marvell 520MHz PXA270-based module provided by Strategic Test [23].

Table 3 Processor module selector matrix for first paper-like prototype device. "all" in the "serial" row indicates SPI, I2C, and UART are all supported.

Vendor	Compulab	Voipac	TI	Strategic Test
Cost	$$	$	$	$$$
Processor	PXA270	PXA270	OMAP	PXA270
Pwr (W)	2	1	1.25	1
Physical	2x SODIMM	SODIMM	large	SODIMM
ROM MB	128	2	32	32
RAM MB	64	64	32	64
GPIO	45	85	16	all
Serial	4 UART	4-all	3-all	5-all
Support	☺	☺	☺ ☺	☺ ☺ ☺

Touch Pad. There are a wide variety of touch sensors available. Early lab tests showed that a stylus on a resistive touch screen was inappropriate for this task, for the following reasons: (a) The resistive touch screen, layered on top of the primary display, adds a parallax issue between the pointer tip and the "ink" on the display. This makes the interface uncomfortable for the user. (b) The resistive touch screen, laminated to a piece of glass as a system sub-component, is much too heavy for a device large enough to display a one-page form (7.7oz). (c) The resistive touch screen is only 87.5% transparent [5]. Because E-Ink displays are reflective, light passes through touchscreens twice, reducing the light by nearly one-quarter. Therefore, we placed a high priority on touch screen inputs that are located behind the E-Ink display, rather than in front of or on top of it. This decision, combined with a non-powered stylus input for form markup (like a pencil on paper), limits the solution to a Wacom digitizing tablet [24].

Wacom digitizers transmit an RF field and listen to the changes in the field to sense the location of the pen. As such, a Wacom digitizer needs to be turned on any time there is potential for writing. Therefore, Wacom-based solutions tend to consume more power than alternatives; however, we believe the other user benefits of the Wacom solution outweigh the power issue for paper-like computing.

Operating System. There are many different types of operating systems, but only a few provide quality developer support, and free drivers applications. This is important for a system development that needs to be as fast as possible with a minimal development team. We decided to go with Debian Linux for reasons of stability, maturity, and driver/kernel availability.

The Rest of the Design

With these key decision points determined, the rest of the system design is summarized below, as shown in Figure 2.

Hardware System. A significant hardware feature we added to this research platform is a high-resolution (3MP) camera sensor, with a small (1.5") Organic-LED-based display used as a camera viewfinder. The selection of the high-resolution camera was to enable pictures of full-page documents to scan them into the device for forms processing. A VGA camera does not have sufficient resolution to take a usable image of a page. The selection of the OLED display as a viewfinder was based on power consumption and ease of implementation.

Our device has only four buttons on the front: two on the right and two on the left. Button functionality is determined by application software, and they can be redundant or unique. Two on each side supports different hand-hold points to make it comfortable for the user. The main purpose of the buttons on either side is to support page flipping forward and back. We implemented force-sensitive buttons, rather than standard press-buttons, to enable the user to press harder in order to move through pages faster.

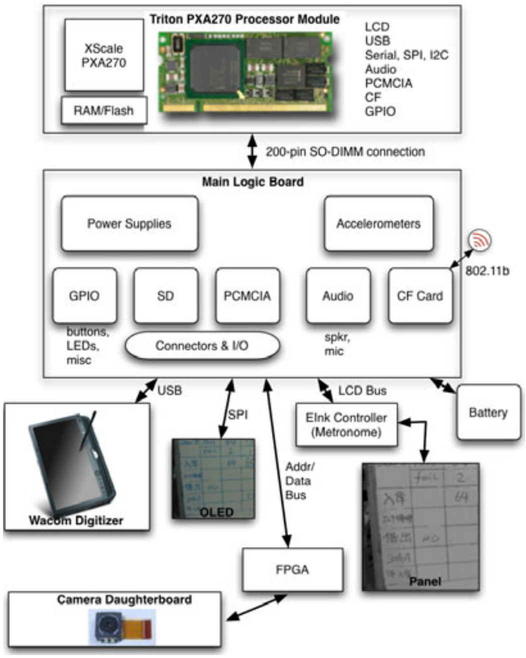


Fig. 2　Block Diagram of a paper-like device.

Connectivity is limited to two ports: a USB host port (which serves USB thumb drives as well as USB-ethernet adapters) and a serial communications port for debugging.

We implemented 802.11b wireless connectivity through a wireless card module inserted into a CompactFlash slot.　A PCMCIA slot internally to the device was pre-filled with a 4GB flash memory card for the OS and applications.　This card is not accessible to the user.　An SD card slot was supported for removable storage, holding user data.

The device can be powered and charged by a +12VDC wall jack, and has a 2-pack of Lithium Polymer 3.7V batteries with a capacity of 1000mAh at 7.4V.

Software Development Environment We used the Linux Debian distribution, and the kernel supported by the selected processor module.　For a number of reasons, we used an old kernel, Debian ARM Linux 4.0, with kernel 2.6.17.　The build environment for the PXA270 processor was a native environment, using the Thecus N2100 Yesbox.　Drivers were general purpose where available, but some custom drivers were required as well (force sensor buttons, OLED display, E-Ink display).

Application code was written in C, Java, Python, and shell/Bash scripts.

Fig. 3　The actual paper-like trial device.

Mechanical Implementation Our goal was to design an enclosure that was as lightweight and thin as feasible, robust enough to withstand actual user testing, and practical within our limited time and budget. The resulting device weighed 1 pound 15 oz., and has dimensions 205 x 250 x 31 mm., and is shown in Figure 3.　Overall, it is approximately the size of an 8.5x11" sheet of paper.

5. User Studies

The authors were able to build 21 units with the design elements described above.　Using these devices, we conducted controlled research experiments, forms testing, and the researchers themselves used the units on a continual basis to gain familiarity with them.

Our research questions included:

1) Is a 9.7" display large enough for working with full-page forms on an electronic paper device?

2) Is the latency of our pen tracking solution low enough that it is nearly as convenient to use as paper?

3) Can our system (hardware/software) emulate paper sufficiently well in a business workflow so that it may eventually replace paper in that workflow?　This

covers ease of use, reliability, user comfort, and barriers to entry.

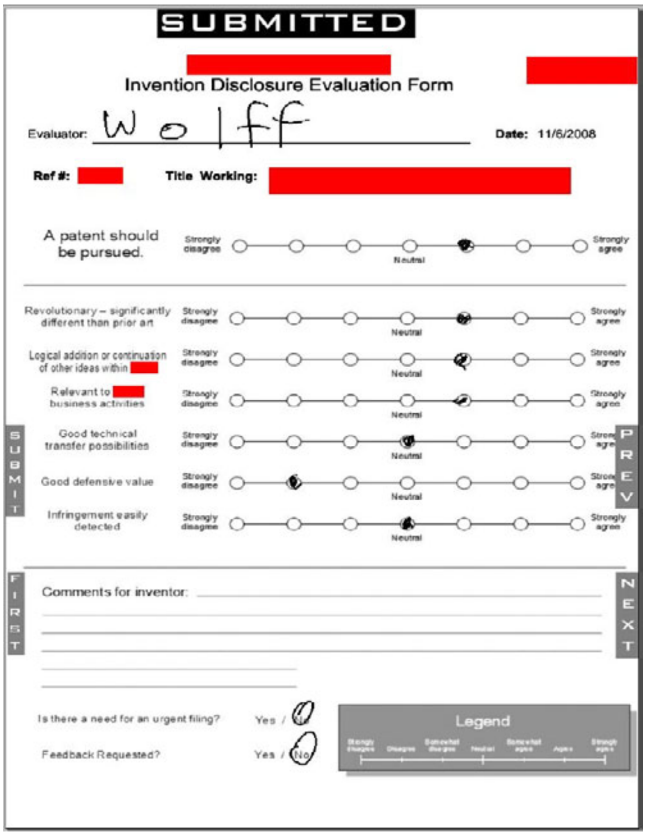
4) What system characteristics worked sufficiently like paper?

5) What system characteristics need more attention to become more paper-like?

Trial 1: Patent Review Committee

A patent review committee meeting consists of a series of presentations by inventors to a committee. After each presentation, each committee member completes a form evaluating such aspects of the invention including novelty and applicability, ultimately to decide whether the time and effort should be spent to patent the idea. This is a paper-electronic workflow hybrid, where the voting is performed on a pre-designed paper form, and entered by hand into an electronic database. Results are distributed and tracked electronically.

A sample paper-based patent review committee evaluation form is shown in Figure 4. We scanned the form into our electronic device as-is (low barrier to entry), and evaluated the effectiveness of our paper-like device in this business workflow environment.


SUBMITTED

[redacted]

Invention Disclosure Evaluation Form

Evaluator: Wolff

Date: 11/6/2008

Ref #: [redacted] Title Working: [redacted]

A patent should be pursued. Strongly disagree — Neutral — Strongly agree

Revolutionary – significantly different than prior art. Strongly disagree — Neutral — Strongly agree

Logical addition or continuation of other ideas within [redacted]. Strongly disagree — Neutral — Strongly agree

Relevant to [redacted] business activities. Strongly disagree — Neutral — Strongly agree

Good technical transfer possibilities. Strongly disagree — Neutral — Strongly agree

Good defensive value. Strongly disagree — Neutral — Strongly agree

Infringement easily detected. Strongly disagree — Neutral — Strongly agree

SUBMIT | PREV | FIRST | NEXT

Comments for inventor:

Is there a need for an urgent filing? Yes / No

Feedback Requested? Yes / No

Legend

Fig.4 An example of the form completed by the patent review committee. Red areas are redacted for the confidentiality of the actual invention reviewed. Not actual size.

For the purpose of this trial, we alerted all members of this committee to the experiment, and informed them that we would provide paper-like devices to half the members for filling out their voting forms, and continue to use the standard paper process for the other half. Mid-way through the presentations, those with paper and those with electronic devices swapped roles. Researchers observed usage models of the devices as compared to paper, recorded impacts of the devices in the workflow, and noted encumbering aspects. A survey was presented to the committee members to get their feedback after the trial.

This trial involved 6 units for a roughly 3-hour test.

Trial 2: Poster Session Presentation Review

This trial was held at an internal research and design event, open only to employees of the worldwide company sponsoring this research. It is a multi-day conference with hundreds of posters and side-meetings, where research and development team members can collaborate, share, and exchange ideas.

During this trial, we conducted a conference survey, where users completed a form on the paper-like devices. It was a fully-electronic workflow, where survey questions were presented on a form on the device, and responses were captured and collected to internal memory (Flash) storage, to be tallied later.

The conference was two days long, and approximately 200 visitors were in attendance. Three units were used.

Electronic Forms Usability Experiment

A key aspect of any paper-like computing device, especially one targeted at business forms workflows, is to determine if the standard sized 8.5x11" form is usable on the 9.7" E-Ink display (with half the active area of a sheet of paper). We experimented with a paper workflow, and used a standard full-page paper form. We scanned the form and displayed it on the electronic paper device. The form was displayed as a single, full page on the device, and we completed the form, and sent it back to a standard printer and printed it at standard size. The form from this process was then scanned into the remainder of the workflow, together with forms that followed a purely paper workflow. This form functioned normally in the workflow. Forms processed by the electronic paper device are just as functional as forms that followed purely paper workflows, for downstream workflow actions.

During this exercise, we recognized that it is possible to eliminate the paper margins of the form to make form features slightly larger.

6. Results

The trials presented a clear view of the benefits and issues of the paper-like device.

Successes — High Level

Display Size is Sufficient for Many Applications This is significant, because it has wide-reaching impact on future devices. Larger display sizes directly relate to cost of the test device, as well as overall size and portability of the unit. Larger sized displays are not always better, when, for example, they are no longer easily carried, or they become cost-prohibitive to use.

Even though the 9.7" E-Ink display is really only about half the size of a regular form on an 8.5x11" sheet of paper, in these test cases, users reported that forms completion was sufficiently functional for this display. The ink resolution was sufficient for the scaled text. Margins/borders were cropped when displayed on the electronic display, but the device bezel provided sufficient margins for holding the form.

It should be clarified, however, that this result applies to forms that are relatively sparse, as in the example form. Denser forms proved to be more difficult to read, and forms that require writing need more space.

Pen Tracking is Acceptable We learned that our fast-pen tracking system was effective for filling out forms in an electronic workflow. The latency and experience of the pen tracking did not interfere with the tasks that the users performed. For those unfamiliar with E-Ink technology, pen tracking was obviously different from pen/paper, but was still effective at completing paper-like tasks.

Finally, some respondents reported that the pen tracking on this device was of even higher quality than typical tablet PC's. The authors did not research this issue further.

The Device was Found to be Useful Sample feedback included: "Forms filling was much more useful than I thought it would be," and "Better, lighter... a PC implies complexity. This was limited and therefore simple." Some test subjects felt that this electronic paper device is "much better" than a typical tablet PC. The reasons given were size and simplicity.

System Characteristics That Merit Greater Attention

Power Management One of the design decisions made, to decrease the overall system development time, was to largely ignore power management in the device. This led to a battery life of approximately 1 hour. This resulted in our devices being tethered to a power cord, thereby limiting portability.

Using a power cord also conveys a feeling of fragility to the user as well, and we observed that this problem caused users to handle the device quite differently from paper.

The design simplification showed a failure in our experiment — any research into paper-like computing must pay strict attention to power management.

Tactile Feedback on Buttons The force-sensitive buttons were more problematic than expected. These buttons are significantly more expensive than standard buttons, have a greater variability from sensor to sensor (more complicated software driver), and provide no tactile feedback to the user.

The authors observed that users expect nearly instantaneous reaction to their actions, or else they grow impatient, often repeating the gesture again. Miller, et al., showed that the maximum time delay from a mechanical action should be no more than 100msec. [15] Repeated pressing of a button caused unwanted or undesirable reactions from the application program.

There are really two issues with this problem: (a) no tactile feedback on the buttons, and (b) a lower-power microprocessor combined with slow-to-update E-Ink display. The combined effect is a response time that is slower than expected.

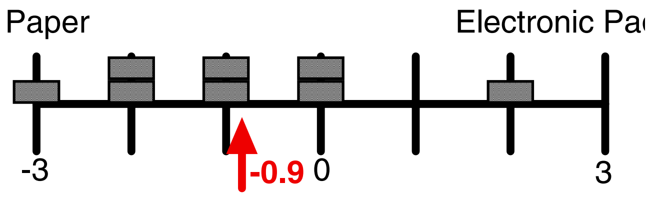
We must provide fast (<100msec) feedback to users of paper-like devices. Standard buttons that click when pressed are preferred. This also reduces accidental selection, as well as impatient double-pressing.

Size and Weight We intended this unit as a research device to investigate paper replacement options, and knew that reduced weight and thickness improves the overall experience. But we did little to minimize these characteristics. Feedback from users indicated that the device needs to be as thin and light as possible, and more effort is merited in this area

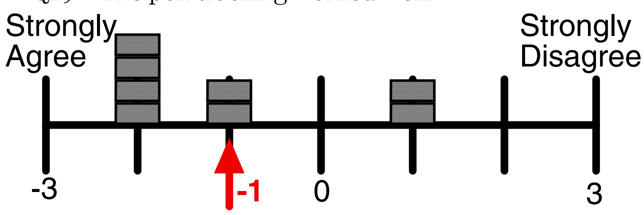
Detailed Results — Patent Committee Trial

The following questions were asked of users after the patent committee trial. Eight people took this survey.

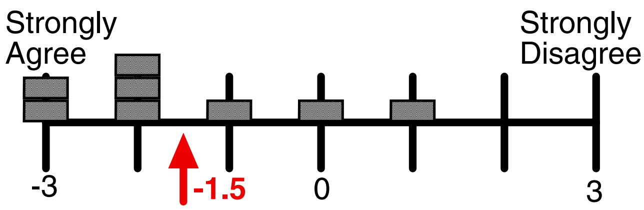
Q1) I prefer to use paper or electronic pad for this type of interaction.



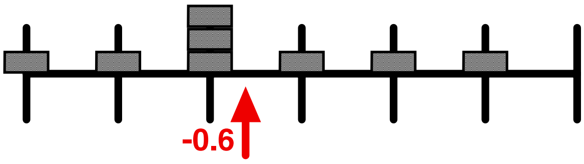
Q2) The pen tracking worked well.



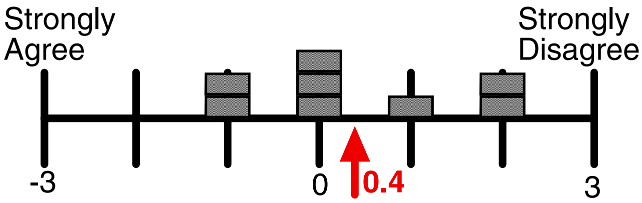
Q3) The electronic pad display was quite readable.



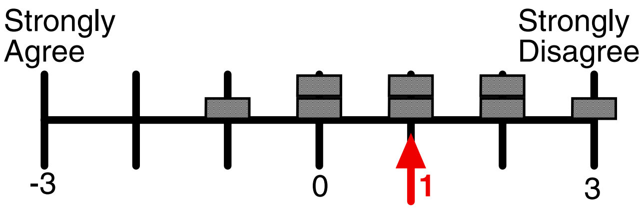
Q4) Writing on the electronic pad felt natural.



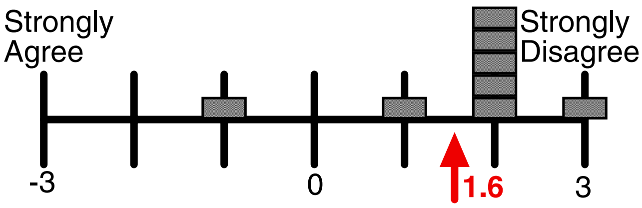
Q5) I wish I could have changed the pen width or pen color.



Q6) I would only use this if it were in color.



Q7) I found this system very difficult to understand and use.



Interpretation of These Results: Test subjects are clearly still more comfortable with paper than with the electronic-paper device. Basic overall preferences are still inclined for paper over electronic devices (Q1). Device frailty may have affected these results slightly.

But users weren't interested in flexibilities that paper affords over the electronic system (Q5 and Q6). And the electronic form itself, even though it was a smaller font on a smaller display, was not a problem (Q2, Q3, Q4, Q7).

7. Future Work

The scope of the user trials should be increased, to apply to more diverse workflows, conditions, and people, and to be used at a real customer site. We are considering a future trial in a daily usage scenario within a university environment. Before we do this, however, we would like to overcome the liabilities uncovered in our preliminary tests. We need more devices, with a more appropriate size, weight, and a better power management system.

We would also like to conduct user trials that correlate fast pen tracking to user's overall paper-like expectations, as compared to other solutions. Stroke erasure presents a large number of other issues, including how to erase (pixels, strokes, different erasers, etc.), and effective ghosting elimination. Finally, effective display of denser forms should be researched.

8. Conclusion

We have presented significant challenges in making an electronic paper device. We focused on forms processing workflows for basic design foundations and our testing, and investigated how an electronic device can augment traditionally paper workflows.

We designed a device to be as paper-like as possible. Primary components were an E-Ink display, a Marvell PXA270 processor, and a simple user interface. Furthermore, driver software was written to overcome many of the drawbacks of electronic paper displays, including support of fast pen tracking and ghosting-reduction algorithms.

We tested the device in trials and user testing to evaluate its paper-like qualities. Although users preferred paper in general (in part due to poor power management, and a device that was larger and heavier than desired), our implementation of many paper-like attributes was successful. Users commented that the device is useful, fast pen tracking was effective, and users were able to work with full-page forms.

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