Designing Pen-and-Paper User Interfaces for Interaction with Documents

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ABSTRACT

Despite numerous predictions of the paperless office, knowledge work is still characterized by the combined use of paper and digital documents. Digital pen-and-paper user interfaces bridge the gap between both worlds by electronically capturing the interactions of a user with a pen on real paper. The contribution of this paper is two-fold: First, we introduce an interaction framework for pen-and-paper user interfaces consisting of six core interactions. This helps both in analyzing existing work practices and interfaces and in guiding the design of interfaces which offer complex functionality and nevertheless remain simple to use. Second, we apply this framework and contribute three novel pen-and-paper interaction strategies for creating hyperlinks between printed and digital documents and for tagging both types of documents.

Author Keywords

Paper Interface, Digital Pen and Paper, Anoto, Hyperlink, Tagging, Framework.

INTRODUCTION

Although the end of paper use has been predicted, traditional paper is still widely used in knowledge work and the use of paper is even augmenting [23]. A field study on notetaking in university learning shows the importance of paper documents: 77 % of a total of 408 students indicated they are taking their notes exclusively on paper; only 8 % reported an exclusive use of a computer [28]. This is mainly due to the unique affordances of pen and paper, including intuitive handwriting and sketching, mobile use, easy navigation, and very flexible spatial arrangements of document pages. A growing amount of research therefore addresses the issue of integrating traditional paper with computing.

Pen-and-Paper User Interfaces (PPUIs), a subset of Tangible User Interfaces, integrate real paper interactions with digital support. The main interaction device is a digital pen, which allows transferring digital ink (handwriting, drawings etc.) as well as additional interactional information (e.g. pen "clicks" on virtual paper buttons) to a computer. A problem with PPUIs is the restricted feedback loop: Digital feedback requires either re-printing an updated version of the PPUI each time an update occurs or using separate channels like audio and visual information on a nearby display. This restricted feedback makes it challenging to design PPUIs that support complex activities and nevertheless remain simple to use. A transfer of the GUI paradigm to pen and paper does not suffice to solve this problem. We argue that interactions should build upon specific paper affordances, which GUI interfaces cannot provide, such as the possibility to physically combine paper sheets.

Prior research on PPUIs introduced interaction concepts for various document-related activities. However, it does not provide a systematic description of the underlying interaction model for PPUIs and gives no general guidelines for designing "good" PPUIs. This stands in contrast to the broader research on Tangible User Interfaces, which suggested several modeling frameworks (e.g. [13, 7, 12]). These however do not focus on the specifics of pen-and-paper interaction. The first contribution of this paper is therefore an interaction framework for PPUIs. It was developed in a systematic and inductive empirical process and defines a set of simple and intuitive core interactions for PPUIs, which can be flexibly combined to support complex activities. The framework supports analyzing existing PPUIs and provides guidelines of how to design a complex PPUI that remains simple to use.

We further contribute novel interaction strategies for the pen-based linking and tagging of documents. These are built on top of the framework and unify the interaction with printed and digital documents, as they allow using the same digital pen both on paper and on a tabletop display while maintaining the flexibility of paper. Furthermore, an interaction concept for the tangible tagging of documents with bookmark stickers is presented.

The remainder of this paper is organized as follows. After reviewing related work, we present the interaction frame-

TEI 2009, February 16–18, 2009, Cambridge, UK.

work for PPUIs. In a next step, we apply this framework and contribute three novel pen-and-paper interaction strategies for the linking and tagging of paper and digital documents. Finally we briefly discuss implementation issues.

RELATED WORK

Technology

Most current pen-and-paper systems (e.g. [9, 32, 24, 29, 17]) rely on the patented Anoto [1] digital pen technology, which supports mobile use. Anoto pens act like ordinary ball pens and leave visible ink traces on paper. In addition, a built-in camera detects a specific dot pattern printed on the paper sheets, which uniquely encodes position information with a very high resolution. Recent research demonstrated how Anoto pens can also be used for pen input on rear-projection screens [5] and on paper palettes that contain physical interaction devices [4]. Other digital pen technologies, such as Wacom tablets positioned underneath the paper documents (e.g. used in [19, 6]) and ultrasonic pen position detection (e.g. used in [20]), are less flexible, since paper sheets must remain within a small area and must not be moved after calibration. Another approach is the camera-based tracking of pen movements and of the positions of paper documents (e.g. [30]).

Existing Frameworks

In the field of Tangible User Interfaces (TUIs), a growing number of publications address concepts and theory (e.g. [13, 7, 12]). However, this work focuses on general TUIs and therefore offers little guidance for the specifics of interacting with a pen in a paper environment.

In contrast to general TUIs, research on Pen-and-Paper User Interfaces (PPUI) almost exclusively focused on developing new systems. An exception is Guimbretière's lifecycle model of transformations between paper and digital documents [9]. This details on temporal aspects of document use but does not cover the issue of how to design the paper interface itself. Yeh et al. [33] define a design space of paper interactions and present a toolkit for the rapid development of PPUIs. However, the underlying interaction model focuses on interactions with single sheets of paper only. Liao et al. [16] explore the design space of pen-based feedback mechanisms in paper-only environments. Holman et al. [11] present base units for interacting with digital paper displays. In contrast to our work, these focus on the physical manipulation of paper displays and not on pen-based interaction. The iServer and iPaper framework [21] presents an extensive model for links between physical and digital documents but does not cover interaction techniques.

Paper-based Annotation and Notetaking

Several systems use real paper as an input medium for annotating electronic documents. PADD [9] and PaperPoint [24] enable users to annotate electronic documents by using their printouts as a proxy. Instead of only adding digital ink annotations as an additional layer to an existing document, PaperProof [29] allows users editing the underlying document itself and therefore analyzes specific pen gestures and handwritten text. Mackay's A-Book [19] uses an underlying Wacom tablet to capture pen input on a paper notebook. Users can access additional digital information on the screen of a PDA when placing it on top of the notebook. While borrowing the idea of paper input, our interaction strategies focus on linking and tagging documents and do not only apply to printed documents, but also to digital ones on a tabletop display.

Paper-based Linking and Tagging

Books with Voices [14] allows users to access audio files from predefined link hot-spots on books, but does not support user-defined links. PaperLink [2] relies on an enhanced pen and supports creating and browsing own links from printed to digital media, but not vice versa. PapierCraft [17] presents pen gestures for creating digital hyperlinks and tags on paper. However, the large number of rather technical pen gestures, which are different from established practices, implicate a higher cognitive complexity than our approach. Moreover, the pen gestures require an additional device for switching between a writing and a command mode. In contrast to our approach, all these systems moreover require separate devices for paper and digital documents. DocuDesk [6] supports creating many-to-many links between printed and digital documents that are positioned on a pen-sensitive Wacom display. While the pen-based interaction for creating links is very intuitive, users have to switch between separate pens for annotating paper documents and creating hyperlinks. Moreover, links do apply to entire documents only and paper documents must be kept flat and within the small surface of the 22 inch display.

Our pen-based association gesture is similar to Pick-and-Drop [22] and stitching gestures [10]. These gestures span several displays or paper and a display, but in applications other than hyperlinking. While stitching does not support paper, Pick-and-Drop has only very limited paper support and does not include document annotation.

Augmented Desks and Blackboards

Augmented desk and blackboard systems have an integrated focus on physical *and* digital documents at the same degree, enabling a very seamless integration of interactions in both worlds. The positions (and sometimes also the contents) of paper documents on the desk are captured with a camera mounted above the desk. Digital documents are displayed on the same desk surface using either projection or a tabletop screen. The Digital Desk [30] supports creating combined physical and digital collages of document snippets. Moreover, users can share their desk surface including physical and digital documents with remote collaborators in real-time. The Designer's Outpost [15] is an augmented blackboard that captures collages of physical post-it stickers on the blackboard. Users can augment these by drawing digital associations between two or more stickers with a digital pen. WikiTUI [31] augments physical books by digital annotations. Users can associate digital material to page areas of the book. By pointing on a link hot spot, the digital annotation is projected onto the table besides the book. However, the camera tracking used in these systems restricts the mobility of paper to interactions on a flat and relatively small surface. While our interaction strategies also include manipulating *digital* information on a tabletop display, the interaction with *paper* is not restricted to this display surface. Users can work on paper documents anywhere in the same room. If no immediate digital feedback is needed, e.g. when annotating paper documents, our system is inherently mobile. Only paper and a digital pen are needed. Data is then stored on the pen for later processing.

AN INTERACTION FRAMEWORK FOR PEN-AND-PAPER USER INTERFACES (PPUIs)

Our interaction framework was inspired by existing PPUIs from related work and by an own inductive empirical process. From three field studies of current paper-based work practices, we derived conceptual activities and syntactic core interactions and integrated these into the framework. The framework both supports analyzing work practices and existing PPUIs and provides conceptual guidance for designing a complex PPUI that nevertheless remains simple to use.

The underlying principle of the framework is an analytic separation between a semantic level of conceptual activities to be carried out with a PPUI and a syntactic level of core interactions that are combined to actually perform these semantic activities. This principle enables PPUIs that are both simple and complex: offering complex functionality while being intuitive and simple to use.

We first describe the results of the field studies and then detail on the framework.

Field Studies of Paper-centric Knowledge Work

The framework is the result of an empirical process, in which current practices of paper-centric knowledge work were studied. Three field studies on learning at universities were conducted (for details see: [28, 25, 27]). These studies assessed the media use, document-related activities, and collaborative practices in lectures and small learning group meetings. A total of 408 students participated to a study on lecture annotations, which was questionnaire-based. A second study analyzed the differences between handwritten and typewritten annotations on slides, which a total of 24 students had made in 9 seminar sessions. In a third ethnographic study, we made hidden and overt observations of 17 learning group meetings with a focus on the document-related activities and collaborative practices. Several formative evaluations of our prototypes with students and colleagues allowed gathering additional insights.

Current Practices

We identified three main conceptual activities of the semantic level that users perform when learning with paper documents: *Annotating* documents, creating or following *links* between two or more documents, and *tagging* documents. The frequent following of (explicit or implicit) links is due to the fact that information is often fragmented between several documents: The task of understanding a particular problem can for example include reading a slide of the course script on the screen of a laptop, making a sketch on a scratch paper at the same time and then formulating a summary on a new sheet of a paper notebook.

Syntactic interactions can be divided into three categories:

(1) Writing on an individual sheet of paper (e.g. annotations, handwritten links and keywords or symbols for tags). Participants often partitioned the available space into separate functionality zones, e.g. reserving the left or right margins of the document for keywords in order to provide for a quick overview on all tags on a page.

(2) Leveraging the material aspect of paper sheets, which can be flexibly arranged in the physical space. Specific spatial combinations of two or more paper sheets convey semantics (e.g. relating documents by putting them into a folder or on a stack or marking important pages with bookmark stickers).

(3) In the co-located collaboration of learning groups, we frequently observed pointing gestures to documents. Very often participants did not only point to one single document but consecutively to several documents or pages in order to express relations between the contents they pointed to.

The Framework

We now integrate and abstract these findings of current work practices with paper documents into a framework for interactions in PPUIs.

The framework distinguishes a semantic from a syntactic level of interaction: The semantic level comprises *conceptual activities*, i.e. the functionality offered by the UI (e.g. the activities of annotating, linking and tagging, which were identified above). The syntactic level comprises *core interactions*, i.e. basic manipulations that are made with the PPUI (e.g. attaching a paper sticker) in order to actually perform these conceptual activities.

Core Interactions

A core interaction is defined as an operation that a user performs by manipulating one or more operands. An *operand* is a page area, for example a document page, a printed “button” or a paper sticker. *Operations* are the following:

- **Inking**: Writing with the digital pen on a page area. This includes free form handwritings and drawings that are digitally captured. Moreover, specific symbols and pen gestures may be performed to issue a command.
- **Clicking**: Performing one or more pen taps on a paper area to issue a command (e.g. on a printed “button” area). This is inspired by pointing gestures.
- **Moving**: Changing the physical location of the page area. This includes picking it up and putting it down as well as flipping pages.

- **Altering Shape**: Altering the physical shape of a page area, for example by bending, folding or tearing it.
- **Combining**: Physically re-arranging or combining two or more page areas. This may be either a loose arrangement (e.g. paper sheets in a binder or on a pile) or a fix attachment (e.g. paper stickers).
- **Associating**: Performing a connecting pen gesture on two or more page areas. This is inspired by consecutive pointing on several items.

The same core interaction may have a different meaning if it is performed on a different type of page area or using a different tool, e.g. a digital eraser.

Table 1 depicts how these core interactions are inspired by interactions with traditional paper and how they correspond to GUI interactions. As GUIs incorporate metaphors of traditional desks, they offer somewhat equivalent interactions for inking, clicking and moving. In contrast, the interactions of combining and associating several paper sheets as well as altering their shape leverage the physical specifics of paper environments and go beyond what is possible in GUIs.

Combining Core Interactions for Conceptual Activities

A critical aspect in the process of designing a specific PPUI is to define which core interactions are used and how they are combined to perform a conceptual activity.

A key finding of our field work was that in traditional paper practice, users often combine several core interactions to perform a single activity. The user may for example attach an indexing sticker onto a document and then write a label on it. PPUIs should account for the rich interactions that are possible with paper and build upon the flexibility of combining several core interactions to perform one conceptual activity. This stands in contrast to a design which is inspired by GUI concepts and therefore uses only the core interactions of inking and clicking (and possibly moving if position tracking technology is used).

	Traditional Paper	**PPUI**	**GUI (foll. [3])**
Single sheet	Writing	**Inking**	Text entry
	Pointing	**Clicking**	Pointing/ Clicking
	Moving	**Moving**	Dragging
	Altering shape (bending, folding, tearing)	**Altering shape**	--*
Multiple sheets	Arranging and Combining	**Combining**	--*
	Subsequent pointing	**Associating**	--*

** No core interaction in itself (performed by combining core interactions).*

Table 1. Comparison of Core Interactions.

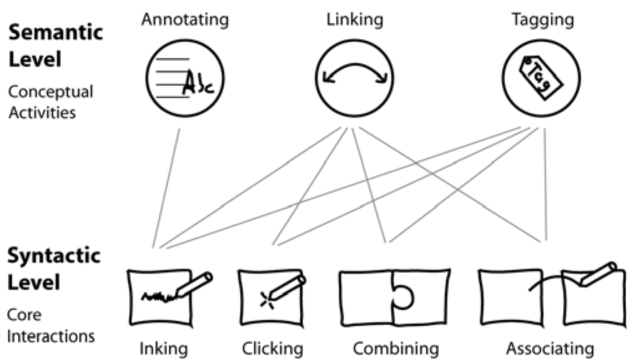

Figure 1. Applying the framework to our scenario. Simple and generic core interactions are flexibly combined to support complex conceptual activities.

Figure 1 depicts how the framework is used for our application scenario, which supports the conceptual activities of annotating, linking and tagging documents. The edges between the upper and the lower level indicate how the user can sequentially combine several simple core interactions in an intuitive manner to perform more complex semantic activities. Our interaction design relies on four core interactions.

Applicability of the Framework to Related Work

In this section, we apply our framework to a representative set of PPUI systems that support users in interacting with documents. We demonstrate that these can be classified in terms of the generic core interactions identified above.

A first class of systems (e.g. [9, 29, 24]) augments paper documents by electronically capturing handwritten annotations (*inking*). ButterflyNet [32] additionally supports creating *associations* between an area of a paper notebook and a digital photo with a pen gesture. Users can access the digital media by *clicking* on this paper area. PapierCraft [17] supports tagging paper documents with pen gestures (*inking*). In a calculator application, Wellner's seminal Digital Desk [30] supports entering numbers by pointing (*clicking*) on a number in an arbitrary document on the desk, regardless if it is printed or digitally projected. Moreover, the physical *combination* of digital and physical documents on the desk can be shared over the distance with collaborators in real-time.

All these conceptual activities are performed with one single core interaction. However, there are also examples, where conceptual activities are supported by a combination of several core interactions. In PapierCraft, the user creates a hyperlink between two paper pages by first highlighting (*inking*) the passages that shall be linked and then *associating* them with two consecutive markings on both pages. Moreover, PapierCraft supports creating physical collages:

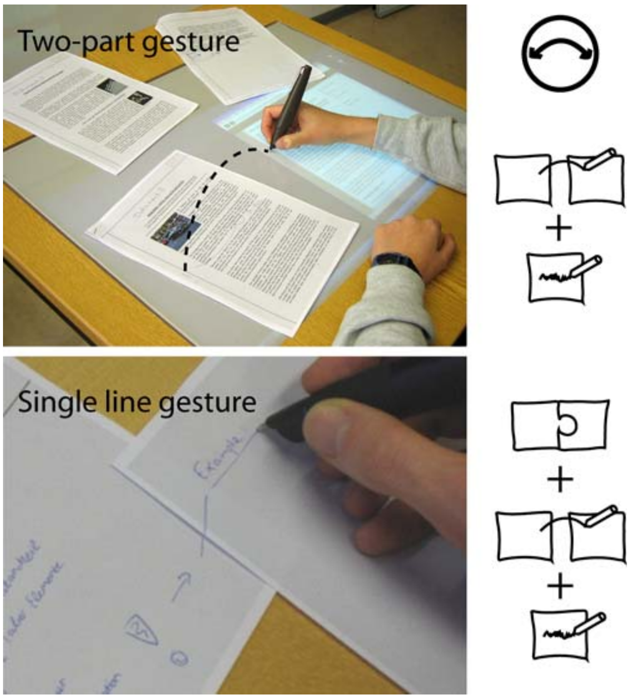

Figure 2. Pen gestures for creating hyperlinks.

A user first physically *combines* two paper sheets by positioning one besides the other in a way that the margins slightly overlap. Drawing an *associating* line then digitally connects both sheets. With the Digital Desk, users can select document snippets with a pen gesture (*inking*) and then *combine* these snippets in a physical and digital collage.

INTERACTION STRATEGIES FOR LINKING AND TAGGING DOCUMENTS

This section applies the framework to our scenario and presents novel tangible interaction strategies for the linking and tagging of printed and digital documents. Following our framework, simple core interactions are combined to support complex conceptual activities.

These interactions are included into CoScribe, a prototype system for annotating printed and digital documents and sharing these annotations with co-workers [27]. Main input device is a digital Anoto [1] pen. This pen behaves like a traditional ball pen on real paper. In addition, it electronically captures the pen strokes made and transfers them to a computer. A digital version of printed PDF and PPT documents (including own and shared handwritings, links, and tags) can be accessed in the CoScribe viewer by clicking on a button printed on each paper page. Further a print toolkit enables printing updated versions of the paper documents.

Cross-media Linking

A cross-media hyperlink is a bidirectional binary association between (a) entire documents or (b) sub-passages in the same or different, physical or digital documents. With the following interactions, users can intuitively create their own hyperlinks in existing documents and navigate through the combined physical and digital hypertext later on.

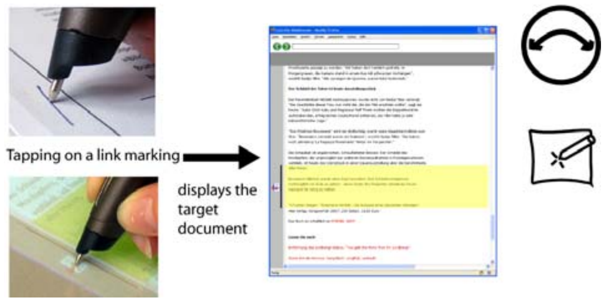

Figure 3. Browsing through the physical and digital hypertext.

Hyperlinks are created with a pen-based association gesture that connects two page areas. Each document contains two types of association areas that decide upon the extent of the association: (1) an area on top of the first page where associations refer to the entire document and (2) a lateral column on each document page for associations from or to sub-passages. Optionally, users can precisely define the extent of a sub-passage by drawing a vertical line marking in the lateral association column besides the sub-passage (core interaction: *inking*).

The user can choose among two variants of the same association gesture: If the documents can be easily repositioned, she rearranges them in a way that the association areas of both document pages overlap (core interaction: *combination*). A single line, which connects both areas, defines the first and second link anchor and creates the hyperlink (core interaction: *association*) (see Fig. 2 bottom). Alternatively, she can split up the association gesture into two parts: The first anchor is defined by holding the pen down on an association area for 500 ms without moving until a click sound is played. A consecutive pen tap on another association area (on the same or another physical or digital page) then defines the second anchor and creates the hyperlink (see Fig. 2 top). The user can optionally add human-readable references to support following links when no computer is nearby. The gestures are recognized in real-time and instant audio feedback is given. A link can be deleted with a cross-out gesture on any marking made for creating this link (core interaction: *inking*).

An important property is that the use of Anoto pens is not restricted to paper documents but is also supported on a tabletop display. Hence, the user can utilize the same pen to perform an association gesture between a paper document and a digital document, which is displayed on a screen. We therefore constructed a tabletop display whose surface is covered with Anoto pattern.

To sum up, a user performs the conceptual activity of hyperlinking by sequentially combining two or three intuitive core interactions. Later on, a hyperlink is followed by clicking on or near a link marking (Fig. 3). This is possible both on a printed document page and on a digital document

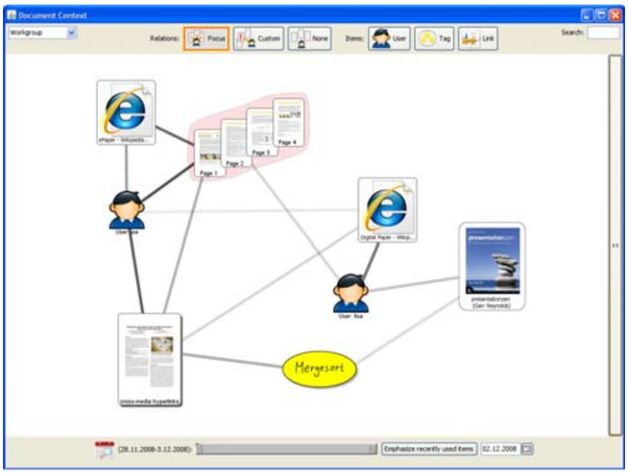

Figure 4. A collaborative visualization of documents, links, tags, and users.

on the display. The target document is then displayed on the tabletop. Moreover, a collaborative graph view provides an overview by integrating hyperlinks from all users (Fig. 4).

Cross-media Tagging

A similar tangible interaction concept supports users in tagging printed and digital documents with keywords.

One or more separate paper cards allow defining and applying tags (Fig. 5). A user intuitively defines a tag by writing a keyword in one of the empty areas provided on this card. After a tag is defined, it is applied using either of the following interactions:

(1) Writing the tag on an association area of a document and enclosing it with a circle in order to mark it as a tag. The tag is automatically recognized from the set of previously defined tags on the Tag Menu Card using handwriting recognition.

(2) Writing the tag on an association area and additionally performing the pen gesture for hyperlinks to associate it with the corresponding area on the Tag Menu Card. This small additional effort ensures that tagging is correctly performed, as it does not rely on handwriting recognition. This is important when no computer is nearby, which could provide feedback on the recognition. The conceptual activity of tagging is thus performed by combining the core interactions of *inking* and *associating*.

In contrast to writing a tag keyword directly on the document, collecting all tags on a separate Tag Menu Card has several advantages. First, the user can immediately access a set of all her tags. In addition, Tag Menu Cards can support operations on the tag set (renaming etc.) which can then be automatically applied to the electronic representations of all documents and their subsequent printouts. Third, research shows that a key factor for the convergence of tags is that the system suggests frequent labels [8]. Yet, computer support cannot be assumed in a paper-only environment without a nearby display. In such a context, the Tag Menu Card fosters similar effects as the suggestion of frequently used tags: users will be inclined to re-using tags already entered on the card wherever possible, since the effort is lower than making a new tag entry.

Once created, tags are displayed in the document viewer and in the collaborative graph visualization, which integrates documents, links, tags, and users (Fig. 4).

Tagging with Tangible Bookmarks

Another interaction concept for tagging documents focuses on the tangible manipulation of paper stickers. It is inspired by traditional paper bookmarks, which are an efficient means for structuring documents, marking specific passages on paper, and quickly accessing them later on.

Digital Paper Bookmarks combine the advantages of paper-based bookmarking with electronic support. They are Post-it like adhesive stickers of different colors, which can be attached to physical pages of printed documents at arbitrary positions. Digital Paper Bookmarks are covered with Anoto pattern and can therefore be labeled with a title using an electronic pen. They are synchronized with the electronic system and serve as electronic bookmarks for these pages.

A user creates a bookmark by sequentially combining three core interactions (see Fig. 6):

(1) *Physically combining* the bookmark sticker with a printed page by attaching it at an arbitrary position.

(2) *Associating* the sticker with the document using the pen gesture which is described above. The bookmark is then available electronically.

(3) *Inking* to provide a bookmark title (optional) by writing

Figure 5. Defining and creating tags with a Tag Menu Card.

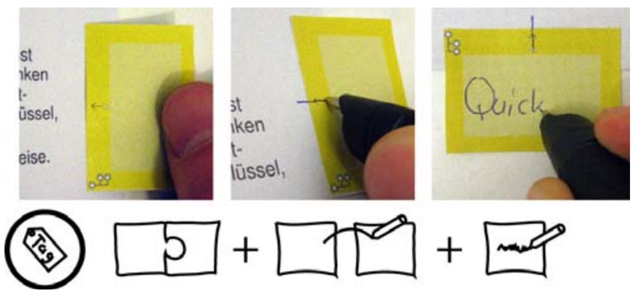

Figure 6. Bookmarking document pages with tangible stickers.

a keyword before or after attaching the bookmark.

Once created, a Digital Paper Bookmark may be modified by sticking it to another position and performing the association gesture again. It can be deleted by removing and writing a cross out deleting gesture on it.

The main interaction is thus the durable physical combination of paper stickers with a document page. In contrast to the more flexible pen-based associations described in the preceding sections, this physical combination has the advantage to offer full feedback in a paper-only environment where no digital feedback channel is available: The position and the contents of paper bookmarks are visible on paper. Moreover, bookmarks support physically accessing the indexed paper pages.

IMPLEMENTATION

The interaction strategies described in the preceding section have been implemented in Java and integrated in a prototype system. We use Nokia SU-1B and Logitech io2 Anoto pens. Our software utilizes the Anoto SDK and allows streaming pen data in real-time over a Bluetooth connection and synchronizing data in batch mode by putting the pen into a USB cradle. Pen gestures are recognized by heuristics. Our prototype uses the Microsoft Tablet PC Handwriting Recognition for recognizing handwritten labels, but the interaction concepts do not rely on handwriting recognition for correct operation, which makes them more robust.

We constructed the Anoto-enabled tabletop display as follows: The Anoto dot pattern was printed onto a HP Colorlucent Backlit UV foil, following the approach of [5]**.** This foil is put between a supporting plexiglass layer of 5 mm width and a layer of 1 mm width, which protects the surface. It is illuminated by rear-projection with a Optoma HD 80 full HD resolution beamer. The diagonal of the display measures 82 cm.

The prototype currently supports PDF, PPT and Web documents. It includes a module which automatically creates printing templates from PDF and PPT files. Users can choose among several printing layouts and can optionally include own or shared annotations to be printed. This tool uses the iText framework [18]. Printouts are performed with an OKI C5900 color laser printer. In order to support linking and tagging Web documents, we developed a plug-in for Mozilla Firefox, which handles pen input on Web pages. It was realized in JavaScript.

SUMMARY AND OUTLOOK

In this paper, we presented a framework for interaction in Pen-and-Paper User Interfaces (PPUIs). This framework analytically separates a semantic level of conceptual activities from a syntactic level of interaction. Based on three field studies of paper-centric document work, we identified in an inductive empirical process core interactions of PPUIs. These core interactions can be flexibly combined in a user interface that offers functionality for complex semantic activities while being simple and intuitive to use.

In a second step, we applied this framework and presented three novel interaction strategies for paper-centric document work, which were designed following the guidelines of the framework. These support hyperlinking and tagging of both paper documents and digital documents. A new tabletop display, which supports input with the same digital Anoto pen as used on paper, provides a seamless integration of paper and digital documents. The same device and the same pen-based interactions apply to a document, regardless if it is printed on paper or digitally displayed on the tabletop. This avoids switching between different devices and interactions and nevertheless maintains the mobility of paper as much as possible.

The novel interaction techniques have been evaluated in two user studies. They showed that these are very easy to use and can be efficiently utilized even by novices after a few minutes of training. Moreover, cross-media hyperlinks enabled participants to perform a complex information retrieval task with collections of interlinked printed and Web documents significantly faster than in a control setting without this interaction technique. A publication with detailed results is currently in preparation [26].

Even though the first evaluation validated our approach, we plan to conduct further longer-term studies with a larger number of users. Moreover, we intend to develop further interaction strategies that put the guidelines of our framework into practice. We are currently constructing a tabletop display with a larger layout space and intend to augment the system with automatic detection of occluded areas and adequate repositioning of electronic display space. This will lead us a further step towards bridging the gap between the paper and the digital worlds.

ACKNOWLEDGMENTS

The author thanks Max Mühlhäuser and Oliver Brdiczka for their comments on early drafts of this paper. Simon Olberding, Roman Lisserman, Sasa Vukancic, Stefan Buhrmester and Michael Stieler implemented parts of the prototypes. This work was funded by the German Research Foundation (DFG-GK-1223).

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