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# Linking print and web based on community needs

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## ABSTRACT

In this paper, we describe the process of using user needs, collected through case communities, to design concepts that link print products and digital services. One of the example cases was an online community, while the other was a traditional off-line community. Users often, perhaps subconsciously, know the strengths of print and web and use the media suitable for their needs accordingly. With a user-centered design approach, it's possible to create new and enticing hybrid media products for user communities with very different backgrounds.

## General Terms

Design, Human Factors

## Keywords

User-centered design, online communities, hybrid media, user experience

## 1. INTRODUCTION

From the consumer point of view, there are no different media technologies; people just have different needs to carry out certain communicational tasks or to entertain themselves. The advantages of web are obvious, but print has properties and characteristics that digital media can never have, and people value paper-based media for its physicality and traditions. New media concepts and hybrid media applications can be created together with user communities, based on their operational, social and emotional needs.

Using a user-centered concept design approach, we developed a few different hybrid media applications, which enable linking the strengths of web and print. We studied two different case communities in their context, generated concept ideas together with the community members and designed prototypes which we also tested with the users.

## 2. STUDIED COMMUNITIES AND HYBRID MEDIA CONCEPTS

### 2.1 Visiting cards for a Photo gallery website

IRC-Galleria (IRC Gallery) is a large Finnish online community and photo-sharing website with over 450,000 registered users and nearly 850,000 unique visitors each week [5]. Over 60 % of Finnish teenagers use the site, and the average age of users is just under 20 [1].

The site has evolved from a photo community into a communication medium, with people conveying information and socializing by commenting each others' pictures. Van House [6] has said that Flickr, another popular photo-sharing website, is *"mostly about images, not images as adjuncts to text"*. In the study, users had said that Flickr wasn't where you had discussions. In contrast, IRC-Galleria—despite its photo-gallery nature—is maybe more text than picture oriented, and its themed communities are currently mostly text-based discussion groups.

Based on studies of the preferences and habits of IRC-Galleria users, collected through interviews [2], observations and a user workshop, we generated ideas for new concepts in a developer workshop, arranged together with IRC-Galleria employees.

Altogether, the workshop yielded 25 concepts. Of those, the five best (ranked by developers) were then submitted for a user review through a questionnaire posted on the IRC-Galleria website. Some concepts were focused only on creating new extensions and features for the existing website, but many ideas also incorporated a print dimension. Based on questionnaire results, uniqueness and easy realization, some ideas were then chosen for prototyping.

One of the ideas developed further as a prototype was a visiting card for IRC-Galleria users. The card contained at least the user's screen name in the IRC-Galleria service, a photograph from the profile and a 2D code for accessing the profile in the mobile version of the IRC-Galleria service (Figure 1). Several prototype designs were made with a different number and selection of information fields on them. These fields included information for example on the card owner's real name, title, home address, phone number and email address. The other side of the prototype card contained another picture from the user's profile.



Figure 1. Prototype visiting card being read.

The purpose of the card was to enhance offline communication: the cards could be given to either old friends or new acquaintances, making it possible for them to find you online. A similar idea was introduced by Staples, who started offering “professional business cards in minutes” that could be used for instance for sharing online screen names and blog addresses [4]. An alternative design in the form of playing cards was also made (Figure 2). It was thought that users might want to collect different cards from their friends, and the purpose of the playing card design was to encourage people to collect the whole series of 52 cards.



Figure 2. Playing card prototypes.

## 2.2 User experience of the card prototypes

The two prototypes were tested with five IRC-Galleria users. The test users were 21- and 22-year-olds, and thus were over the average IRC-Galleria user age. They felt the cards were meant for people younger than them. The pictures in the prototype cards featured teenagers, which might have affected the outcome. The reaction was also probably due to the fact that the online service and its extensions are most popular among teenagers. Some users also would have wanted to use the cards for more official purposes, but thought the cards looked too informal and had too much of the look and feel of the IRC-Galleria service.

The test users wanted to have control both over the graphical appearance of the cards and the information that they contained. They were ready also to accept advertisements in the card if it

made the cards cheaper and if they were given the possibility to choose the advertisers.

There were some worries about information getting into the wrong hands through the visiting cards. This concern, often related to the physical nature of the product, was voiced also at other stages of the study. In the user questionnaire, respondents were worried about other people printing or ordering their photographs. Although the same information and the same photographs are available online for everybody to see, they seemed to become more real once they are printed. The prospect of information getting into the wrong hands seemed to become scarier and even more likely in the users’ minds when a physical product was involved, even though in reality the potential audience is much bigger for an item posted online.

There was a difference between the proposed use for cards in the traditional visiting card format and cards in the playing card format. Cards in the traditional format were considered suitable for storing information for a short time, whereas the cards in the playing card format were seen as a fun thing that could be collected and stored.

Price was an important issue and affected the users’ opinion on whether they would order them. They were also concerned of the costs of connecting to the Internet with their mobile phones when using the 2D code.

Generally 2D codes were not considered necessary in this context. It was a common opinion that the process of reading the codes should be made much easier; otherwise they thought that it didn’t make sense. It should be noted, however, that the opinions might have been more favorable if it had been easier to read the code in the test situation. The demo code contained probably too much information compared to its size and the lighting conditions were quite poor in the test setting. There was some initial excitement because of the codes, because they were a new thing for the test users. Although the users hadn’t encountered 2D codes before and didn’t recognize them at first, most of the users would have approached them by photographing the code.

## 2.3 Socially produced newsletter for football club volunteers

The other studied community was a group of volunteer workers of a Finnish football club Myllykosken Pallo (MyPa). In this case, there was a mutual need for the enhancement of communication between the volunteers and the organization. Together with MyPa, we came up with the solution of a widely available community newsletter, the content of which was to be created by the volunteer community itself (Figure 3).



Figure 3. Story board description of the socially produced newsletter for MyPa volunteers.

We recognized two kinds of important end user groups. On the one hand, there were the volunteers themselves, who would use and create the content. The volunteers are a loosely organized group who lead their duties in smaller groups, in their free time, without need for professional experience. Technically, their experience is often limited, restricted usually to mobile phone and some e-mail use. On the other hand, there is the MyPa organization, which would like to use some kind of an enhanced communication medium to strengthen the relationship between the organization and its volunteer workers.

The 2D code application was added to the concept idea so that mobile phones could be used to enroll in different kinds of courses and happenings while reading information on the subject in the newsletter (Figure 4).



Figure 4. Using the 2D code to check additional information from the web while reading the newsletter.

From the content creation point of view, the concept of socially created print product is very fresh. In this case, the motivation for “volunteers creating content by themselves for themselves” concerned primarily the strengthening of the existing community. The organization, obviously, encouraged the volunteers to take

responsibility for this activity because its own resources are limited, whereas volunteers seemed to be genuinely interested in social content creation.

From the technical point of view, the smooth combining of a content creation system and a newsletter publishing process was a challenge. The interface of the system would be used by the volunteers to create content, and it should produce the printed newsletter with as little hassle and cost for the organization as possible. Without a functioning system, there is no possibility to create content socially so that it can end up in print “looking like print as it should be”.

The tested publication system was a piece of open-source software, which would be relatively cheap for the organization to tweak, but the system could also be a piece of stand-alone software, or part of a more complex content management system executed in the server side. These kinds of systems already exist [3], but what’s important is that their structure for data does not easily lend itself to the newsletter’s internal structure, nor do they usually have a ready interface to print products, but are linked to specific distribution platforms.

We recognized that transferring traditional print publishers’ duties to the users themselves doesn’t currently happen as smoothly as content creation in the digital world. This means the content created on the Internet will too easily remain there, even if it had potential cross-media uses in printed form.

## 2.4 User experience of the publication system interface and the use of 2D codes

The user tests included both content creation with a prototypical Internet-based system, and evaluating different newsletter formats and functionalities applying 2D codes.

Users considered the content creation system usable after some training and it was perceived to contain more functionalities than expected. Adding images to the articles and modifying them was considered a difficult task.

The test persons mainly perceived that the system was easy to use. Positioning the phone for reading the code was considered to be difficult. SAM (Self Assessment Manikin) ranking showed that the emotions connected with the usage of the code were considered to be mainly positive but not very strong.

This kind of enrolment was considered to be better than making a phone call or using a computer. It is sometimes difficult to contact people by phone and to know what the best time for making a call is. The problem with the computer is that it should first be turned on and a computer is not always available. Tested users were also interested in knowing whether it is expensive to use the services.

## 3. CONCLUSIONS

Although consumers do not make a difference between different media technologies on a conscious level, the development of a successful media product by combining different media technologies is a challenging task. The starting point needs to be in realizing the known and hidden user needs and developing product concepts based on them. The cases reported in this paper prove that user-centric product concept design can and should be

used in developing hybrid media products. And that testing the new idea early in the design phase with actual users guide the developers to concentrate on relevant issues from the users' viewpoint.

One of the strengths of print media is its physical nature. In communities a socially, together, created magazine can make the society more coherent and dynamic. There is a hidden creative potential in different kind of communities that can be taken into use if only they are given the suitable tools that combine the advantages of different technologies in the virtual and physical worlds.

#### **4. ACKNOWLEDGMENTS**

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# DriftShift: Tracking Shared Paper Use with Pens on Tabletop

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## ABSTRACT

Existing sensor fusion techniques blend data from multiple sensors to improve the accuracy of object positioning. We outline a new technique called DriftShift which uses a position fixing technique as a bridge to transfer drift errors between different objects' coordinate systems. Our technique suits tracking problems in which different physical objects are intermittently juxtaposed as part of existing real-world practices, notably pen and paper or paper and table. We illustrate this technique in paper-based systems by positioning a pen using a dead reckoning wireless inertial sensor with respect to a piece of paper marked up with Anoto pattern. We effectively transfer the inertial drift out of the pen's coordinate system and into the paper's coordinate system. This transfer uses an Extended Kalman Filter to differentiate between the position error introduced by the inertial drift and the user's physical movement of the paper. The DriftShift technique could be further nested to introduce coordinate systems over a larger scale. For our domain this could introduce driftless accuracy for off-paper pointing and gesturing to tabletop-scale shared displays.

## Keywords

Pen tracking, paper tracking, inertial sensors, Anoto.

## 1. INTRODUCTION

Electronic support for paper use traditionally explores digitizing activities of writing and inscription. Such approaches tend to encourage technology development which can use everyday paper-based writing activities whilst exploiting digital systems alongside. This emphasis on writing tends to create technologies which are excellent at detecting the relative relationship between pen and paper during periods of contact between them. However, existing technologies are typically poor at detecting activities with pens and paper that are not related to the specific act of writing, but rather relate to other uses of these artifacts within the broader social context. There are many such meaningful and common behaviours around everyday paper use, for example detecting gestures with pens to items on paper or elsewhere; showing pieces of paper to others; demonstrating movement using pens or paper to others;

displaying thinking through tapping or sucking a pen; and many more.

Our particular interest in keeping track of between-contact pen and paper use stems from work as part of the MiMeG e-Social Science node studying and designing for 'data sessions'. These sessions are conducted by groups of social scientists analyzing video sequences, typically around a table together, whilst using individual paper copies of talk transcripts. Thus they involve multiple pens and paper in broad tabletop-scale environments.

Our goal is to support such situations across networks for distributed research teams. However, it has become clear through earlier studies [2] that supporting distributed data sessions between two groups of analysts creates disjoint interactions between local and remote groups [8]. This character of disjointed distributed work is partly due to the difficulty of referring to onscreen and on-transcript events for both co-located and remote participants simultaneously. Yet, at certain moments, designing actions to be seen by remote participants becomes critical to supporting coordinated work between sites in real time. Thus, detecting and preserving the spatial relationships between collocated groups and distributed groups in these situations is an interesting prospect. Nonetheless, supporting everyday movements with pen and paper locally, whilst capturing and illustrating these movements remotely, is no small challenge. Key to this challenge is finding a method of tracking and identifying pen and paper in groups, particularly in situations where these may be locally shared, swapped or shown between one another. Current relative tracking techniques such as Anoto pattern detection or magnetic sensors on pens are poor at providing sufficient information about paper and pen use to detect or represent such activities in isolation. In this paper we outline an alternate technique for sensing a broad range of pen and paper uses not specific to writing. We particularly focus on uses whose identification requires more than a relative knowledge of pen movement with respect to paper, instead demanding a sense of the relationships between multiple pens and multiple pieces of paper across a broader surface such as a tabletop. Such approaches have corollaries with recent research looking at new forms of off tabletop interaction techniques [5].

Tracking multiple objects in three dimensional space requires some positioning technique using one or more sensors. The primary technical challenge for tracking uses of pen and paper is detecting movements at the resolution with which pen use occurs – typically at least of the order of millimeters for handwriting. Most solutions to digitizing writing overcome this resolution problem by detecting the relative contact point between pen and paper, either through pressure on a solid surface backing the paper (tablet), or special paper (e-Ink, Anoto). Tracking systems which detect the location of the pen (e.g. through magnetic fields or image processing) also tend to focus on the pen-paper contact or else retain little sense of the location of the paper with respect to the pen over time. It is difficult to track pens on their own in three dimensional space because position sensors which work indoors are in isolation too inaccurate to track at writing resolution due to cumulative drift errors over time (e.g. inertial sensors) and may also require significant technical configuration of the environment (e.g. ultrasound transmitters in the ceiling and a receiver on the pen [3]). To obtain the necessary accuracy to keep track of pens and paper in three dimensions we would currently need a heavyweight solution of multiple sensors fusing data to improve the accuracy of pen or paper positioning. In other domains such techniques attempt to ‘cancel out’ dead reckoning cumulative drift error such as odometry using an additional position fixing technique such as GPS outdoors or ultrasound indoors [7].

In this paper we therefore describe a new technique called DriftShift we have developed which provides a first step towards table-scale pen and paper tracking. Our technique operates by displacing tracking error out of a pen’s location sensor and into the paper and then potentially the table’s coordinate system, giving accurate positions for the objects of contextual relevance. In the following section we outline our generalized technique and then give a brief analysis of its effectiveness during our initial exploration of the necessary technologies.

## 2. DRIFTSHIFT

We outline a new technique called DriftShift which, instead of canceling or correcting errors with additional sensors, uses a position fixing technique as a bridge to transfer drift errors between different objects’ coordinate systems. Our technique suits tracking problems in which different physical objects are intermittently juxtaposed as part of existing real-world practices, notably pen and paper or paper and table. We use the contact moments between the objects (and their sensors) as an opportunity to ‘shift’ the accumulating tracking error from the former object’s coordinate system into the latter object’s coordinate system. We illustrate this technique in paper-based systems by positioning a pen using a dead reckoning wireless inertial sensor with respect to a piece of paper marked up with Anoto pattern. We effectively transfer the inertial drift out of the pen’s coordinate system and into the paper’s coordinate system. We discuss later how it will be equally possible to further conduct the same process between a piece of paper and a tabletop, given a positioning and identification technique for the paper with respect to the table (e.g. using image processing).

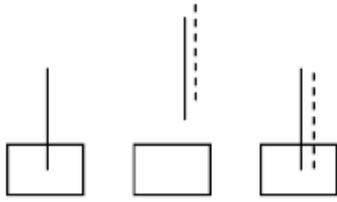
Put formally, the operation of the technique is outlined below:

1. Source object S (pen) is positioned using a local cumulatively drifting sensor technique (such as spatial inertia or wheel odometry).
2. Destination object D (paper) is provided with the means to position S with respect to itself, with a non-drifting sensor technique (such as image processing or ultrasound)
3. Each time  $t$  that S comes into contact with D, a vector comparison is made between the new position  $p$  (determined using D’s sensor technique at time  $t$ ) and with the predicted contact position  $p'$  (determined using D’s sensor’s previous position determined at time  $t'$  and adding vector  $v$  determined by summing vectors from S’s sensor technique between times  $t'$  and  $t$ ). An overall vector offset  $O$  is observed.
4. The scale of cumulative offset  $O$  are analysed each time  $t$  to determine whether they are achieved by drift in S’s sensor accuracy or by physical relocation of object D. For this step to work well, we require that the scale of displacement of object D in space between times  $t'$  and  $t$  is of a significantly different order than the scale of displacement caused by the drift in the sensor.
5. A D-displacement-scale offset is detected, we assume D has been moved and the position of D is updated. If an S-displacement-scale offset is detected, we assume S’s sensor has drifted and the origin of S’s sensor is recalibrated.

In our example case, the DriftShift error transfer uses a Kalman Filter to differentiate between the position error introduced by the inertial drift and the user’s physical movement of the paper. These positions are sufficiently different if the drift magnitude during the typical time period between pen-paper contact contrasts with the magnitude of the user’s physical paper movement on a surface. At the end of an ‘off paper’ period, if the location of the pen given by the inertial data is significantly different from the recently acquired Anoto paper location, we can assume that the paper has moved. We then take the difference between the estimated (inertial) and actual (Anoto) location as the approximate movement vector of the paper (or the error introduced in the inertial sensor). This can be summarised by the following two opposing scenarios, although the Kalman filter will cope with both simultaneously as long as the paper movement and drift are of different scales.

### 2.1 Correcting Drift

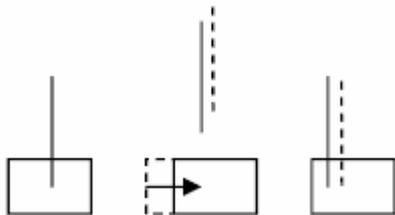
The pen is picked up from the piece of paper. Its point of contact in Anoto space is recorded. The inertial sensor attached to the pen continually updates its position with respect to this point. Over time it gets more inaccurate – where the pen is (solid line) differs increasingly from where the sensor positions it (dashed line). When the pen comes back into contact with the unmoved paper, the Anoto reading reflects a small difference from what would be expected by summing the starting Anoto position with the inertial vector. We use the Anoto reading to correct for the inertial drift.



**Figure 1.** Tracking the pen while the paper remains still

## 2.2 Tracking Paper

The pen is picked up from the piece of paper. Its point of contact in Anoto space is recorded. The inertial sensor still gets more inaccurate. The user moves the piece of paper. When the pen comes back into contact with the paper, the Anoto reading reflects a large difference from what would be expected by summing the starting Anoto position with the inertial vector. The difference is sufficient that the movement is treated as a paper movement. The stored paper location is corrected by subtracting the inertial vector over the movement from the Anoto distance over the movement. Note that this value includes an error of the magnitude of the pen's drift. However, this error is introduced into the paper's coordinate space not the pen's.



**Figure 2.** Tracking the paper while it moves

This technique allows us to locate the pen accurately in space with respect to the paper, supporting absolute tracking of the pen within the now slightly drifting paper coordinate system, allowing uses such as tracking mid-air gestures and pointing to the paper. In the next section we outline our first attempt at realizing this approach and preliminary difficulties and opportunities we have encountered in exploring the idea.

## 3. IMPLEMENTATION

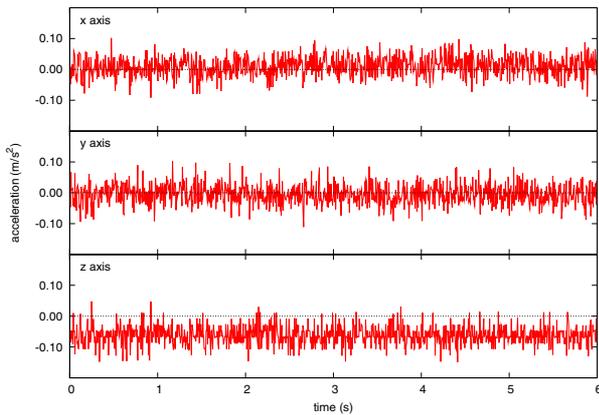
Thus far we have implemented a basic version of our technique using pen and paper. We have yet to evaluate its effectiveness at supporting a 'real' pen and paper application because there are a number of enhancements outlined below required to achieve a fully working system.

Our system operates across the five-point algorithm outlined in the previous section. We have used an Anoto-enabled pen

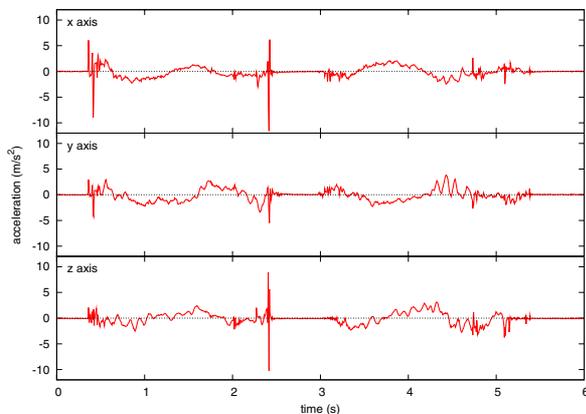
(Nokia SU-1B) as the source object *S* and Anoto-enabled paper as the destination object *D*. For *S*'s drifting sensor, the Anoto pen has attached to it a small wireless inertial sensor, for which we use the Wireless Inertiacube 3 from Intersense. The wireless sensor allows free and relatively unencumbered movement of the pen whilst offering a good basic accuracy with an accelerometer, gyro and magnetometer combination for each of three spatial axes. The data from these sensors is streamed over a bespoke wireless protocol to the corresponding receiver which is connected to a laptop. For *D*'s accurate non-drifting sensor we used the built-in image processing enabled by the camera in the Anoto pen nib which detects the pen's location on the paper. In order to obtain this data, we had to adapt the firmware on the pen to allow real-time streaming of coordinate data over Bluetooth from the pen to the laptop. We then wrote some software on the laptop to receive data from these two sources. We also wrote a Kalman Filter to act as the drift manager, which then uses moments of streamed Anoto data to differentiate between drift and paper movement. We made three assumptions to allow immediate exploration of our technique:

1. The paper does not move during pen contact. It would be possible to detect this event using a combination of the Anoto inertial data and correct accordingly, but we have not implemented this as we have yet to find a situation in which the paper moves during contact with the pen (although no doubt there are occasions where marking paper involves 'pulling' paper underneath a pen nib to make marks).
2. The paper does not rotate, only translate. Again, this is clearly not the case and is indeed much more likely than the paper moving during contact. Any changes to the orientation of the paper are an important part of assessing the vectors of movement of the pen and paper. However, rotation is not easily identifiable with the Anoto pens. There should be a means of extracting the rotation based on the raw Anoto image processing data which inspects the unique pattern around the centre. However, this raw orientation data is not available over the Nokia streaming firmware API. Thus without the complex step of rewriting Nokia firmware to obtain this data, in the shorter term perhaps we might use the inertial compass data from the top of the pen as an indicator of rotation of the bottom of the pen.
3. The frequency of pen contact with the paper is relatively high. If we were to not use the pen on the paper for large amounts of time with a heavily drifting inertial sensor, the tracking data would become increasingly inaccurate. However, informal observations of the situations we are most interested in indicate that marking up paper during 'data sessions' is a frequent occurrence. We are particularly encouraged by seemingly 'pointless' uses of paper such as 'doodling' during use. Such contacts between pen and paper, whilst 'off-task' will nonetheless improve the accuracy of our tracking.

We lose significant amounts of accuracy in position using inertial measurements because we need to integrate the acceleration data twice to obtain positional estimates. Our initial output from the inertial sensor can be seen below.



**Figure 3.** Noise from the inertial sensor when stationary, showing an approximate maximum magnitude of  $0.1\text{m/s}^2$



**Figure 4.** Using the inertial sensor to detect movement, the kind of acceleration data we are able to obtain across three axes.

It can be seen from Figure 3 that the noise involved in the inertial sensor is significant at standstill. Furthermore, there are acceleration biases in the data caused by errors in mapping the axes of the sensor to the axes of the space. This can be seen most clearly in the offset from zero of the z-axis data in Figure 3, which displays readings taken after correcting for gravity. Currently this means that despite obtaining very good velocity data during movement (Figure 4), our Kalman Filter currently has too much sensor drift to cope with to be able to distinguish from paper movement. This is the reason why typical inertial sensors have time correction information such as independent ultrasonic and RF beacons to manage their acceleration noise levels [1], and we anticipate that adapting an ultrasonic solution to help track the pen will sufficiently support our approach to be feasible. Thus our explorations indicate that a wholly ‘infrastructureless’ solution with sufficient accuracy to achieve our goals is currently not possible, although we believe we can achieve a solution without also introducing RF signals into the environment. We have developed a low-cost ultrasonic beacon system which should suit the purpose well [6].

## 4. CONCLUSIONS & FUTURE WORK

The example we have outlined will sufficiently track the location of Anoto paper in space without the need to annotate it with cumbersome tracking functionality or to constrain its placement in any way. However, it will not allow us to track multiple pieces of paper across a surface. We suggest that nesting the DriftShift technique to further displace the drift error out of the paper’s coordinate system and into a broader context could be a future development over a larger scale. For example, we might use an infrared tracking tabletop surface such as the recently released Microsoft Surface platform [4] to position and identify pieces of paper. When the paper as a source object comes in contact with the destination object of the table, this will allow the paper’s location within its own drifting coordinate system (generated originally by the pen’s sensor fusion with the paper) to be compared against the table’s positioning sensor and differentiated, shifting the drift into the table’s coordinate system and accurately positioning multiple pieces of paper and pens with respect to one another. For our domain this could introduce driftless accuracy for off-paper pointing and gesturing to tabletop-scale shared displays.

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# PaperProof: A Paper-Digital Proof-Editing System

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## ABSTRACT

Recent approaches for linking paper and digital information or services tend to be based on a one-time publishing of digital information where changes to the printed document become isolated from its digital source. Structural information which is available when authoring a digital document is lost during the printing process making it difficult to map interactions within the physical document to the corresponding elements of the digital document. We identify the necessary requirements for an integrated digital and paper-based document lifecycle and present our solution which supports a seamless transition between digital and physical document instances. PaperProof is presented as a paper-based proof-editing application that exploits our new approach for mapping pen-based interactions with paper documents to the corresponding operations in the digital document instance.

## 1. INTRODUCTION

Recent developments in the area of interactive paper in terms of enabling technologies, supporting infrastructures and applications have demonstrated the potential benefits arising from an integration of paper with digital services and information. Multiple projects have focused on paper-based physical interfaces for digital services where actions on paper documents are mapped to their digital counterparts.

The realisation of paper-digital document integration normally involves two main steps. First, a digital device has to bridge the gap between a physical paper document and the digital world. Nowadays, there exist several technologies that enable the linking from printed documents to digital information including digital cameras, ultrasonic receivers, magnetic field sensors, barcode readers, RFID antennas and Anoto's Digital Pen and Paper technology [2]. Regardless of the hardware solution used, the general approach is to couple a physical object with an identifier—a Globally Unique Identifier (GUID) in the case of barcodes and RFID tags or areas for ultrasonic positioning technologies, magnetic receivers and Anoto-based devices—and transmit that information to a computing device. Second, one needs to define a link between a user action on paper and the corresponding digital service. The information available on the physical paper document should therefore be captured and translated into a digital language.

A variety of research projects and commercial products have investigated how to enable this kind of paper-driven digital services. Wellner's Digital Desk [30] is a camera-based approach, while the Wacom Graphics Tablets [28] make use of a weak magnetic field applied to the writing surface and the mimio Xi [13] is a product based on ultrasonic positioning. Barcodes have been used in a range of projects in the past, while RFIDs tags are quite common in more recent ubiquitous computing applications such as the mediaBlocks project [25]. The Anoto technology seems to be more flexible and may be easily integrated into the paper document space since it is essentially based on regular paper and a digital pen. In the last few years, multiple projects and applications have been realised based on Anoto technology including PADD [6], ButterflyNet [31], Hitachi iJITinLab [7], EdFest [15], PaperPoint [24] and Print-n-Link [17].

However, so far, most of the approaches for linking paper and digital documents tend to be “one-way solutions” which means that they generate interactive paper documents from a digital instance rather than enabling seamless transitions back and forth between the digital and paper representations of a document. The main focus is on the interaction from a paper document to some sort of digital service, neglecting the information which was available during the authoring of the digital document instance. If we take into account the authoring process, it is easy to realise that a large amount of structural and possibly also semantic information about the content of the document is available within the authoring tool. At the time of printing, information about the structure of the document as well as the different elements that the document consists of (paragraphs, images, tables, etc.) is usually lost when the document is transformed into a graphical representation without any structural metadata. To give an example, this research paper was authored using a  $\text{\LaTeX}$  editor and transformed into a PDF document which could then be printed on paper. The important thing to note is that from a printed version of this document we no longer have access to the explicit structural information present in the  $\text{\LaTeX}$  authoring tool.

Therefore, the linking between paper and digital documents is often bound to the concept of areas only and does not provide easy access to elements within the digital document that the user actually interacted with on paper through actions such as underlining or circling

(e.g. a word or a paragraph). This capability would require links between the physical and digital document instances based not only on IDs or the physical (x,y) position of elements within the printed document, but also based on structural information available in the source document. By having such a mapping back to the original structural elements, we could select single logical elements in a printed document and perform actions on the corresponding digital counterpart.

In previous work, we defined a model for the seamless mapping between a digital document instance and its printout [29]. Based on this model, we developed the iDoc framework which is capable of combining the metadata from both digital and printed documents, thereby enabling a true two-way interaction. In this paper, we present PaperProof, an interactive paper application based on the open source OpenOffice authoring tool [18]. PaperProof exploits the features of the defined model and provides a real-world application of the iDoc infrastructure. It proposes a solution for the common problem of automatically integrating corrections and annotations done during the paper-based proof-reading of a document. A generic approach to dynamically map a physical position on paper to elements within the original digital document instance is proposed and the infrastructure capable of managing the physical representation of digital documents on paper is outlined.

In Section 2, we motivate the need for an integrated paper-digital proof-editing system and present different existing approaches for mapping between paper and digital document instances. Section 3 introduces the requirements for paper-digital document representations and the corresponding interactive proof-editing system. In this section, we also classify existing approaches based on these requirements. In Section 4, we present our vision for an integrated paper-digital document lifecycle. Sections 5 and 6 outline our approach for binding a digital document to its paper versions and the mapping from paper back to the digital document. The PaperProof proof-editing application that validates our paper-digital mapping solution is presented in Section 7. Some details about the implementation of PaperProof are given in Section 8, while Section 9 compares it to existing approaches. Finally, concluding remarks as well as some comments about future extensions are provided in Section 10.

## 2. BACKGROUND

By observing how people work while creating documents, we can identify three main phases: i) the authoring phase, which normally is performed on a computer and results in a first draft of the digital document, ii) the proof-reading phase which is often done on a printed paper version and iii) the editing phase where annotations from a printout are transferred back to the digital source document. During the proof-reading phase, two types of handwritten markup are common—editing instructions and comments. The phases are often iterative and concurrent. This means that, in the extreme case, multiple “reviewers” may be annotating different paper copies of the same document concurrently, while one or more authors continue to work in parallel on dig-

ital versions of the document. In this case, the process of inserting annotations and corrections into the digital document becomes even more difficult since the author has to deal with corrections from multiple users which may also overlap. There are cases, especially in a concurrent scenario, where digital aids such as a change tracking mechanism offered by an authoring tool might be used. Even if these tools are only bound to the digital document and have no connection with the paper instances, they share the concept of annotations as a building block of the proof-reading system.

Document annotations have been extensively analysed in the past and their role in increasing the value of the source document has been recognised. As outlined by Marshall [11], different systems have been implemented to support the annotation process of digital information. Sellen and Harper [21] point out how the process of annotating and marking up is one of the key affordances which often makes paper the preferred medium for interacting with a document. System architectures and applications for different types of paper-based annotations have been described in the past including, for example, a framework for cross-media annotations [4].

In this section, we provide a brief overview of existing digital and paper-based approaches for annotating documents, focussing on projects using digital pens or Tablet PCs.

### Adobe Acrobat

The prevalence of Portable Document Format (PDF) documents as a document exchange format in combination with the possibility to easily read them on any device and any operating system, places Adobe Acrobat[1] at a privileged position for the digital proof-reading of documents. Adobe Acrobat Professional allows a reviewer to annotate a document either by means of free-form annotations as written on a Tablet PC or with regular textual annotations entered via the keyboard. The notes are stored as separate metadata and may be printed together with the document. A highlighting feature is provided in order to emphasise specific parts of a document. Other functionality includes text and graphical editing.

The latest version of the Acrobat tool also supports shared reviews by means of network folders, WebDAV servers, or Microsoft SharePoint Services and the corresponding synchronisation mechanism. Authors of different comments may be identified by their notes’ style attributes (e.g. colours). If a document was originally authored in Microsoft Word and exported as a *tagged* PDF or if it has been drawn in AutoCAD and then transformed into a PDF with the AutoCAD PDFMaker, Acrobat provides the possibility to export the annotations and to import notes, comments and even text elements added to the source document. However, while it is convenient to use the stylus on a Tablet PC for simple free-form annotations, more complex operations, such as deleting a word or changing some text, require the use of a mouse and keyboard.

## Microsoft Ink Annotations

With the Windows XP Tablet PC and Windows Vista operating systems, Microsoft introduced the concept of ink annotations. Ink annotations were first introduced in the Windows Journal tool which allows a Tablet PC user to draw on the screen with a stylus and insert free-form annotations. This feature is now also part of Microsoft Office tools such as OneNote and Word, where ink annotations can be inserted in three different ways: (i) an *ink drawing* rendered into a dedicated canvas, (ii) an *ink note* rendered on top of existing content as a free-form annotation, or (iii) an *ink comment* consisting of a side note with the free-form annotation.

Similar to Adobe Acrobat, the widespread use of Microsoft Office also places this tool at a privileged position for the proof-reading of digital documents. However, even though Microsoft Office provides a change tracking mechanism, the free-form notes supported by ink annotations are not integrated within this mechanism and changing the layout of the document can cause problems. For example, adding or removing content before or after the annotations may destroy the alignment between annotations and content. Thus, reviewers who want to collaboratively proof-read a document using the change tracking functionalities still have to use mouse and keyboard interactions.

## XLibris

XLibris [20] is a project that supports the *active reading* of documents. The system was built for an early Tablet PC prototype. It proposes an annotation system based on free-form annotations which tries to mimic interaction with regular paper documents. The user is presented with a scanned version of the paper document which may be annotated with a pen. The annotations do not have to conform to any form or structural constraints and are inserted into the documents based on the pen's (x,y) position without considering any components of the anchored elements. The algorithm on which XLibris is based preserves the position of the annotations based on a reflow mechanism, even if the document is viewed with different fonts, different aspect ratios or on different devices. The annotation reflow functionality anchors the notes at a particular position within the digital document. Therefore content may be moved without losing the connection with the annotated element. In XLibris, each annotation is attached to a pagination-independent location. However, the document's content is static and may not be changed.

## PenMarked

An annotation tool designed for teaching and correcting student assignments is PenMarked [19]. The system enables a teacher to annotate student assignments in computer programming with comments and scores using a Tablet PC. Assignments are regarded as fixed documents since there is no collaborative authoring. Therefore annotation reflowing is not supported. Marks are processed by means of Optical Character Recognition (OCR) technology and collected to summarise the re-

sults of the assignment. Even if the correction of programming assignments might be effective on a fixed paper-like representation, this task often requires interaction with the digital source which is not supported by the tool.

## ProofRite

ProofRite [3] is a word processor developed by Conroy et al. based on Anoto technology. It supports the merging of annotations made by different users on a printed copy of a document with the digital source document. After making corrections on the printed document version, users may continue editing the digital document. ProofRite also supports the reflowing of the markings according to changes made by the users. The main purpose of ProofRite is to automatically transfer any paper-based annotations to the corresponding digital document rather than to interpret editing markup such as the deletion of a word and execute the corresponding operations on the source document. Also, ProofRite does not provide any change tracking functionality within the digital document.

## 3. REQUIREMENTS ANALYSIS

The process of proof-reading a document is a complex procedure involving multiple tasks and may span the digital and paper worlds or be a purely digital operation. The affordances of paper documents with respect to their digital counterpart have already been introduced and paper has been identified as an important medium for the proof-reading of a document. However, we should not forget the tools for digital editing which can be extremely helpful, especially in collaborative authoring. For this reason, we introduce the concept of a mixed paper-digital proof-reading system and analyse its requirements.

To be effective, such a system must be fully integrated within the publishing process. In other words, users wishing to proof-read a document on paper should be able to use their standard tool for the authoring of the digital document and print out an interactive paper version of it without much effort. As soon as the process of proof-reading is finished, the *integration* of the corrections done on paper into the digital source document should be automatic. Therefore, our goal is to have a *proof-editing* system rather than simply a proof-reading system which only records changes to be made as annotations without actually performing them.

The interaction with the system should be as intuitive as possible and cater for different categories of users and tasks. There exist multiple forms of proof-reading or copy-editing a document. Standards such as the BS 5261 proof-reading mark revision [8] proposed by the British Publisher Association or the ISO standard 5776 [9] are used by professional publishers and should be supported, but also more open approaches used by non-professionals should be taken into consideration. By generalising the idea behind these standards as well as informal markup commonly used by authors, all of the symbols used may be grouped under the same concept of gestures. Therefore we believe

	Adobe Acrobat Professional	Microsoft Office + Ink Annotations	Xlibris	PenMarked	ProofRite
<i>Paper-digital integration</i>					✓
<i>Automatic publishing</i>	✓	✓		✓	
<i>Free-form annotations</i>	✓	✓	✓	✓	✓
<i>Proof-reading integration</i>	✓	✓	✓		✓
<i>Annotation reflow</i>		✓	✓		✓
<i>Handwriting recognition</i>		✓			
<i>Multiple reviewers</i>	✓	✓			✓
<i>Gesture support</i>					
<i>Change tracking</i>		(✓)			
<i>Semantic mapping</i>	(✓)				

Table 1: Comparative requirements analysis

that a gesture-based approach should be supported by every paper-based proof-editing system. Moreover, the system should support the definition of new gestures and the assignment of operations to the corresponding gestures to support different forms of markup. For example, an inverted caret (∨) might be interpreted as an insert operation to be executed within the digital authoring tool.

As soon as the number of operations increases and the corresponding corrections are executed automatically within the authoring tool, it becomes difficult for the users to retrieve and understand the changes that have taken place within the digital source document. For this situation, we can use the change tracking functionality that is available in most modern authoring tools. The tracking of changes within a digital document becomes more difficult if the document has been proof-read by multiple reviewers, both on paper or in digital form. Multiple reviewers should be supported by identifying their corrections and highlighting them in a distinctive manner within the digital document. Again, in most modern authoring tools, this functionality is already provided and a paper-digital proof-editing system should also support it when working with paper documents.

In Section 2, we recognised a second form of markup that is commonly used to simply provide comments to the authors rather than editing instructions. We refer to these as free-form annotations and it is important that a paper-digital system should also be able to integrate paper-based as well as digital free-form annotations into the digital source document. Further, in the case of paper documents, it should be possible for handwritten free-form annotations to be integrated automatically into the digital source document as digital text based on handwriting recognition technologies.

Once annotations have been inserted into the source document, users should be free to edit and update the document or to display it in a different format without losing the association of an annotation to the part of the document that it annotates. This is known as *annotation reflow* functionality and should be offered by the proof-editing system.

To fully support many of the requirements outlined above, it is necessary to have a *structural mapping* from paper back to document elements within the digital au-

thoring tool. By this, we mean that it should be possible to associate logical elements within a paper document such as paragraphs, words, table entries and images with their digital counterparts and to do so at different granularity levels. Hence, it should be possible to select an entire section, a paragraph within it, a word or even a single character and apply an operation to the corresponding element within the digital document. Furthermore, it is important that the representation of the element on paper should be fully independent from its digital representation so that the mapping can be maintained over different versions of both the digital and printed instances of a document. Thus the mapping from a sentence within a paper document back to the corresponding structural element within the digital source document should still apply even if that document has been edited since it was printed.

## Comparative Analysis

The solutions presented in Section 2 already support some of the requirements outlined above as summarised in Table 1. The only real paper-digital system is ProofRite while the other tools are based on a paper-like representation of a digital document on a display. The majority of these tools support the publishing process since it is reduced to just displaying the document. Xlibris requires a special transformation of the source document, while there is currently no support for the automatic publishing of ProofRite documents. Some of the requirements such as the insertion of free-form annotations or the reflow of these notes are supported by many systems. Note that PenMarked and the Adobe Acrobat tool do not support annotation reflow since they are based on static documents.

Even if annotations are supported by most of the mentioned systems, there is still very limited support for handwriting recognition which is currently fully supported only by Microsoft’s ink annotations. As soon as the interaction becomes complex and multiple authors or reviewers are involved, Adobe Acrobat, Microsoft Office and ProofRite are the only applications that can still handle the annotations. The concept of gestures is not supported by any of the presented systems and only Microsoft Word makes use of the integrated change tracking, even if there is no way to interact with the tool through the ink annotations.

Most approaches do not take into account any of the structural information present at authoring time. Once a digital document is printed on paper, it is no longer possible to directly access the digital counterpart of a structural element printed on paper, nor is it possible to automatically establish a link between the printed elements and the original objects of the source document. The only system which partially supports this interaction is the Adobe Acrobat tool which may export some of the corrections made on the PDF into the source authoring tool, but only if the PDF has been generated with special tools for tag insertion. ProofRite has similar problems since it tracks the position of annotations on paper and anchors them to the elements (i.e. words) rendered at the same position within the digital document. The created link is based only on the physical positions of the annotations and anchored elements and not on the link's semantic meaning. This implies that if the format of digital elements is changed after printing (e.g. different font size), the physical (x,y) positions of the elements may differ from the ones recorded at printing time and ProofRite is no longer able to link the correct elements. This lack of structural information is a major weakness of most existing systems. The solution for this problem is to retain structural information when generating a physical rendering of a document.

#### 4. THE DOCUMENT LIFE-CYCLE

The requirements analysis already highlighted the major steps in the production of interactive paper documents and stressed the need to support the bidirectional and continuous transition between paper and digital media. By analysing the life-cycle of a document in digital and paper media, we can identify four essential stages that form a logical and cyclic workflow starting and ending within the authoring tool as shown in Figure 1.

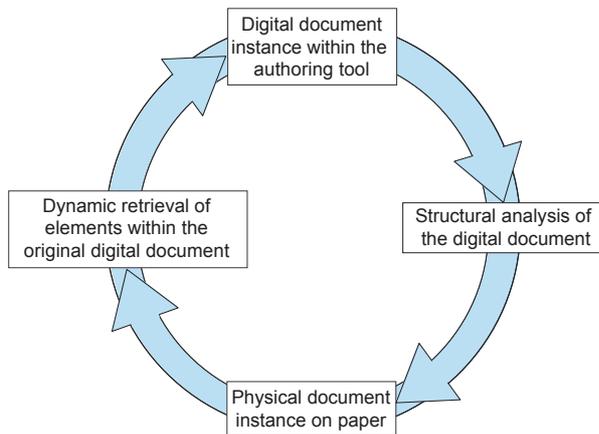


Figure 1: Document life-cycle

Nowadays, the first stage usually involves a digital authoring tool (e.g. Microsoft Word, OpenOffice Writer). An author normally uses such a tool to create an initial version of the document. Since we want to support paper-based proof-editing, the next step is to print out the document. In order to bridge the semantic gap

between paper and digital media, another important stage must be executed before the printing process—the structural analysis of the digital document. This step consists of extracting the document's structural information (e.g. sections, paragraphs and words) and making it persistent in order to be retrieved at a later stage while interacting with the physical document instance. For this reason, we enrich the publishing process in order to store additional information for single structural elements within the authoring tool. The third stage is the generation of the paper document which will be used for the proof-editing phase. At this point, the fourth stage is executed and, depending on the user's actions on paper, the digital elements are retrieved and the mapping between the physical and digital instances is performed.

As shown in Figure 1, the semantic analysis of the digital document and the dynamic retrieval of the digital elements are the core elements enabling a bidirectional mapping between printed and digital document elements. The definition of such a mapping mainly involves three tasks: (i) the implementation of a tool which intercepts the publishing flow within the authoring tool and analyses the structural information of the document prior to it being printed on paper, (ii) the design and implementation of an infrastructure that manages mixed physical and digital information coming from the two document instances and (iii) the design of a tool to effectively retrieve a digital element from a physical (x,y) position, resulting in a bidirectional mapping between printed and digital document versions.

Our vision of an integrated document life-cycle gives users the freedom to perform the same type of operations on either a printout or a digital version on screen. In the remainder of this paper, we will explain how this goal was achieved and provide more details about the mapping between digital and physical document instances. The approach described in the following is based on a specific Page Description Language (PDL), the Microsoft XML Paper Specification (XPS) [12], but is general enough to be used with other PDLs.

#### 5. FROM DIGITAL TO PAPER

The transition between digital and paper document instances must preserve the structural information available at authoring time. We enable the persistent storage of this information by applying two mechanisms that we call *structure highlighting* and *PDL annotation*.

##### Structure Highlighting

In order to extract the structural information from a digital document, we introduce the concept of a *highlighter* that uses graphical shapes as structural containers. During the publishing process, the document tree is analysed, information about the document structure is extracted and shapes are defined for every high-level object in the tree. These shapes are drawn around the different objects highlighting them and the document is transformed into a physical representation through an XPS virtual printer. Since the highlighting shapes are part of the document, they are not lost during the printing process and may be retrieved from the XPS file.

We have defined several types of highlighters depending on the structural elements that they are representing. The abstract class `Highlighter` is responsible for the activation of the connection with the authoring tool and for the printing of the document to an XPS file. For highlighting specific elements, several implementations are provided: section, table, graphics and text. They all provide a different implementation of the abstract class, adding specific methods for the execution of the highlighting process at the different structural levels. In order to better understand the concept, Figure 2 shows the result of highlighting a document at paragraph level: each paragraph of the first section has been enclosed by a polygon shape responsible for collecting all the words that are part of the paragraph.

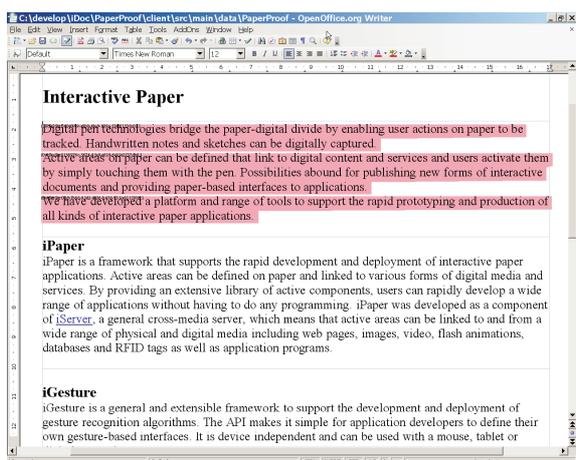


Figure 2: Highlighted paragraphs

## Dynamic Granularity

The document tree may contain structural information at different granularity levels. The solution of tracking single elements within a document, from section to character level, by highlighting them and extracting their positions is not a feasible solution, since it requires a large amount of space and computation time. A more appropriate approach is to make the operation dynamic by grouping smaller elements into higher level granularity sets (e.g. characters into words or words into paragraphs) and tracking the subelements only when they are really needed. Such an approach was first presented in [29].

The idea behind this approach is to have the possibility of referring to the logical object representation at different levels of granularity. For this reason, the concept of an element has been defined according to a composite design pattern [5] as shown in OM notation [14] in Figure 3.

An `Element` belongs to the `AtomicElements` collection if it does not contain any lower-level objects. Otherwise, it is inserted in the `CompositeElements` collection and a `ComposedBy` relation is created for each of its child elements.

Consequently, the element storage is first defined only at a high-level granularity, so that a small number of

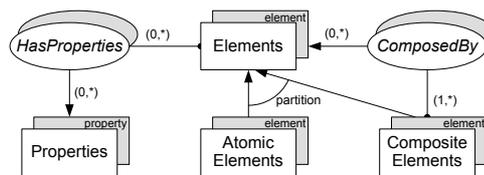


Figure 3: Element model

objects have to be analysed in a first step. For the analysis of elements at lower-level granularity, a dynamic approach is taken. Since the composite pattern creates a hierarchy of elements that also represents important structural information, we start from the highest granularity level and, if necessary, compute the subelements down to the desired granularity in a recursive manner. Therefore, the system offers a dynamic storage model for elements that refines the granularity of the stored structural information on demand.

## PDL Annotation

After the highlighting phase, elements that are structurally linked together are enclosed and presented as a single shape but the physical representation of the document does not yet provide a structural model. Moreover, the shapes interfere with the rest of the document content. In order to remove the shapes and insert structural information about the enclosed elements, we introduce the concept of *PDL annotations*. By using an *XPS snippet extractor*, we can track all highlighted shapes, extract physical information about their position and retrieve the elements that they contain.

To understand how the annotation process works, we first introduce the structure of an XPS document, focussing in particular on its `<Glyphs/>` and `<Path/>` elements. Note that a similar approach may be used for other PDLs.

An XPS file is basically a ZIP archive containing a set of XML files (one file for each physical page) describing the structure of the page at a graphical level. All fonts and images are also part of the ZIP archive. `Glyphs` elements are used within XPS to represent a sequence of uniformly formatted text. The most important attributes are the `OriginX` and `OriginY` defining a glyph's position on a page, the `FontUri` representing the font to be used, the `Indices` representing the distance between single characters composing a glyph and the `UnicodeString` containing the actual text content of the glyph. An example of an XPS file containing a `Glyphs` element is shown in Figure 4.

```
<Glyphs
  Fill="#ff000000" FontRenderingEmSize="14.7206"
  FontUri="/Documents/1/Resources/Fonts/
    083FE3E4-5F00-4F2E-85D9-B082CEBD4F5E.odttf"
  StyleSimulations="None" OriginX="96" OriginY="109.92"
  Indices="87;258;393;286;396,34;87;396;381;381;296,30;3"
  UnicodeString="PaperProof"/>
```

Figure 4: XML representation of a `Glyphs` element

`Path` elements are used to add vector graphics and raw images to an XPS page. They contain a `Data` attribute describing the geometry and position. Figure 5 shows an example of an XPS file containing two `Path` elements rendering a blue rectangle with a black border.

```
<Path
  Fill="#ff0000ff"
  Data="F1 M 95.04,131.84 L 224.96,131.84 224.96,
    203.84 95.04,203.84 z"/>
<Path
  Stroke="#ff000000" StrokeThickness="4"
  StrokeLineJoin="Miter" StrokeMiterLimit="8"
  StrokeStartLineCap="Round" StrokeEndLineCap="Round"
  Data="F1 M 95.04,131.84 L 95.04,203.84 224.96,
    203.84 224.96,131.84 z"/>
```

Figure 5: XML representation of `Path` elements

Since an XPS document is simply a ZIP archive, it is easy to add new content to it without interfering with the correct display of the paginated format. We store the information about the structure of the document retrieved from the highlighted shapes in a separate XML document, called `references.xml`, and add it to the XPS archive. The annotation process consists of the following steps:

1. Create an XML node (`Section`, `Paragraph`, `Table` or `Graphic`) for each highlighted shape and add a child `Shape` containing an XML description of the space covered by the highlighting shape.
2. Extract the physical information for each `Glyphs` and `Path` node of the XPS file and check if it resides within a highlighted shape.
3. If the `Glyphs` and `Path` nodes are part of the highlighted shape, create an `XInclude` node as a child of the element representing the highlighted shape within the `references.xml` file.

The `XInclude` element is a link to an external XML element referenced by an XPath expression in the `href` attribute [27]. By using such an approach, we reduce the amount of redundant information within the XPS document, since the original XML nodes are not replicated in the `references.xml` file. An example of an annotation for a section containing multiple paragraphs is shown in Figure 6. In this example, the `XInclude` link refers to the first XPS page `1.fpage`.

By means of these XPS annotations, XPS elements at any granularity level may be mapped back to the original digital document in a dynamic way as described in the next section.

## 6. FROM PAPER TO DIGITAL

In order to enable mapping back from any physical document instance to the corresponding digital elements, we define a *document mapper* exploiting the advantages of the dynamic granularity process during the publishing process and an *element finder* to retrieve the corresponding digital element within the source authoring tool.

```
<section
  id="iDoc:Sec:9603a909-66b7-419c-ae3c-4038762161d2"
  PageNr="1" secName="Introduction" secRelIndex="1">
  <paragraph
    id="iDoc:Par:ef39a647-bb4-45c0-bd81-7c42adcdd2fd"
    parent="iDoc:Sec:9603a909-66b7-419c-ae3c-4038762161d2"
    relativePosition="1" secRelIndex="1">
    <xi:include href="1.fpage" parse="xml"
      xpointer="element(/1/2)"/>
    <xi:include href="1.fpage" parse="xml"
      xpointer="element(/1/3)"/>
    <shape>
      <polygon>
        <point><x>74.4</x><y>160.0</y></point>
        <point><x>74.4</x><y>144.0</y></point>
        ...
      </polygon>
    </shape>
  </paragraph>
  <shape>
    <rectangle>
      <upperLeft>
        <point><x>72.96</x><y>140.0</y></point>
      </upperLeft>
      <size>
        <width>648.0</width><height>146.8</height>
      </size>
    </rectangle>
  </shape>
</section>
```

Figure 6: Annotation of paragraph elements

## Document Mapper

Once the PDL annotation has been successfully performed, it is possible to build a hierarchy of elements which recursively contains other elements as outlined earlier in Figure 3. We defined all the structural elements (`section`, `paragraph`, `word`, `character`) as objects that extend the base abstract class `Element`. This class contains the basic fields and methods common to all elements. These element objects build a hierarchical structure defined through the `getElements()` method computing an element's child elements as illustrated in Figure 7.

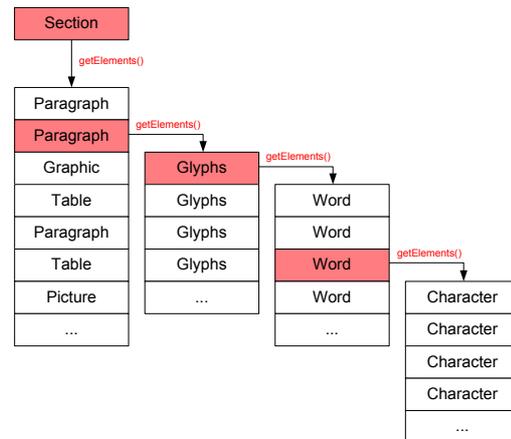


Figure 7: Element hierarchy

To retrieve a section's elements, `getElements()` first highlights the elements contained within the section in the authoring tool and produces the highlighted XPS file. The XPS file is parsed, the XML representations of the subelements are retrieved and the corresponding objects are created. Note that for graphical objects there is no implementation of the `getElements()` method since a raw image does not contain other elements.

For **Paragraph** elements, `getElements()` returns a list of **Word** objects. The method first creates **Glyphs** objects according to the glyphs node contained in the XML representation of the paragraph and calls the method `getElements()` for each of the **Glyphs** objects. The subelements of a **Paragraph** are therefore the words composing it.

To get the position and shapes of a paragraph's words, several operations have to be computed locally on the XPS file. As outlined before, the XPS **Glyphs** element stores the physical coordinates of the beginning of the glyph, the URI of the font used to render the text, the textual content of the glyph and a list of indices. By combining all this information, it is possible to access the dimensions of every single word composing a glyph and also of all the characters composing a word. This approach is used in the `getElements()` implementation for **Paragraph** and **Word** elements.

## Element Finder

When printing the document, the highest possible granularity level is retrieved from the digital document and an XPS file is created and annotated. In order to retrieve a digital element from paper, an *element finder* extracts the information about selected elements from the XPS file and forwards it to a *physical-digital adapter* that retrieves the corresponding digital elements in the source authoring tool.

Depending on the elements selected on paper, the `findElements()` method provided by the element finder returns one or more elements. The system relies on the gestures that a user performs on paper to understand their intentions. For instance, the system does not know whether a user wants to select an entire word or only some of its characters. Therefore, we implemented a simple algorithm for the automatic resolution of the granularity level.

Starting from the highest element granularity (i.e. section), the system first checks how many elements have been selected by the gesture. If more than one element is found, we are already at the correct granularity level and the elements are returned. If only one element is found, it might be because the desired granularity level is lower than the current one and the paragraphs, tables and graphics contained within the section have to be analysed. This process continues recursively until the lowest possible granularity level is found. If, during this process, all subelements of a parent node are selected by the gesture, it means that the gesture has to be applied at a higher granularity and the system goes back to the parent level. The resulting algorithm is outlined in Figure 8.

Since the retrieval of elements implemented within the `findElements()` method has to be general enough

```

Input: shape S on paper
Output: selected digital element(s)
Set Granularity level G at the highest possible value
while not at lowest granularity do
  search elements within shape S with granularity=G
  if all elements at granularity G found then
    | G = Parent.granularity
    | return Parent
  end
  else if only one element E found then
    | G = E.granularity
  end
  else if more elements found then
    | return all elements found
  end
  else
    | no elements found
    | return nothing
  end
end

```

Figure 8: Dynamic granularity algorithm

to be adapted to every authoring tool, we decided to use a very simple method where the relative position of elements within their parents is taken into consideration. When the elements are published within the XPS repository, a reference to their parent and their relative position is inserted along with all the information about their content and physical position. Figure 9 shows a snippet of the XML file which semantically annotates the XPS. It is possible to see the relationship between a section and its first paragraph.

```

<section
  id="iDoc:Sec:9603a909-66b7-419c-ae3c-4038762161"
  pageNr="1" secName="Introduction" secRelIndex="1">
  <paragraph
    id="iDoc:Par:ef39a647-bb4-45c0-bd81-7c42adddd2fd"
    parent="iDoc:Sec:9603a909-66b7-419c-ae3c-4038762161"
    relativePosition="1" secRelIndex="1">
    ...
  </paragraph>
  ...
</section>

```

Figure 9: Relative element position

This additional information is used in the retrieval phase, according to a two phase operation. To better explain the retrieval process, let us have a look at an example outlined by the sequence diagram in Figure 10. In this example, a digital pen is used to select a word in a printed document and we want to get access to the corresponding digital element within the authoring tool.

Starting from the coordinates received from the pen, the document mapper calls the `findElements()` method of the **ElementFinder** class. This method retrieves from the XPS annotations the physical elements bound to these coordinates. As explained above, it might happen that no elements are bound to this position causing the need to analyse the digital document at a finer granularity level. In this case, the highlighting process is started and the **Publisher** generates a new version of the annotated physical document containing more detailed structural information. The second phase runs in the opposite direction. The counting feature is implemented in

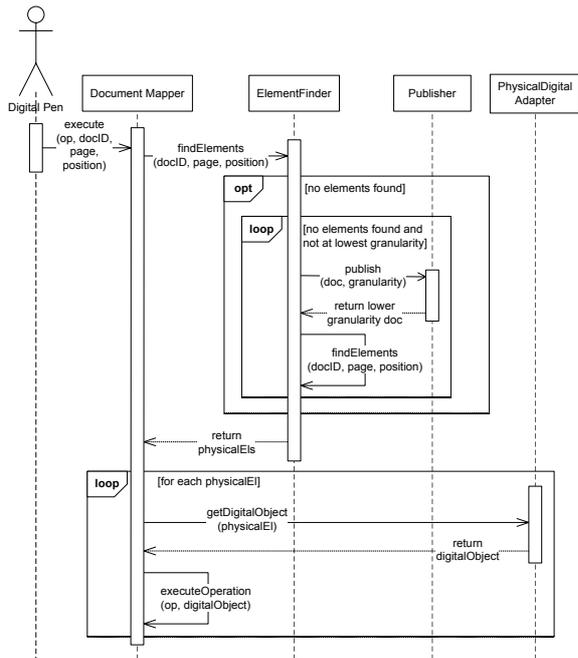


Figure 10: Paper-digital sequence diagram

the `PhysicalDigitalAdapter` class which, given one or more elements retrieved from the XPS file, gets the corresponding digital elements from the authoring tool by calling the `getDigitalObject()` method. By using the example above, the section found in the first phase is retrieved within the authoring tool and, based on the relative position of its children, the correct paragraph and word within the paragraph is found. Once this process is completed, the digital document is retrieved and the action defined through the digital pen on paper may be executed within the source authoring tool.

The supported structural mapping opens up a wide range of possibilities of interaction between digital and paper documents. In the next section we introduce the PaperProof proof-editing application that we have developed based on the presented mapping approach.

## 7. PAPERPROOF

Many authoring tools provide a way to track changes within a document. Whenever this functionality is used changes are made visible to the user rather than simply being executed on the text. They are therefore considered as tentative operations that can later be individually accepted or rejected, either by the same user or by other document editors in the case of collaborative authoring.

PaperProof makes use of the OpenOffice change tracking functionality in order to translate operations that a user performs on a printed OpenOffice document with a digital Anoto-based pen back into the digital document instance. Figure 11 shows the physical and digital representations of a text document processed by our system. On the left-hand side, the marks are done on paper

with a digital pen and, on the right-hand side, they are transferred into OpenOffice.

Once a document has been printed on paper, the proof-editing process can start. In order to execute commands in the PaperProof system, the five operations **insert**, **delete**, **replace**, **move** and **annotate** have been defined.

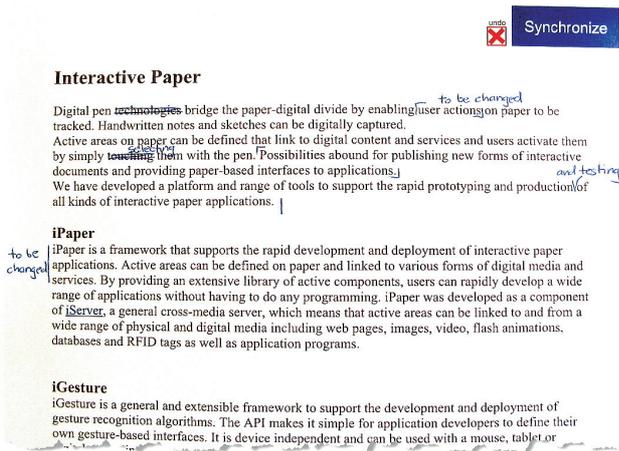
It is possible to apply operations at different granularity levels such as section, paragraph, table, graphics, word or character. One author might want to delete a whole paragraph, while another author just wants to correct a typo at the character level. An annotation might be made for a whole section or just for a particular word. The different granularity levels are automatically recognised by PaperProof using the approach outlined in Section 6.

In order to initiate commands for the desired operations, PaperProof makes use of gestures. Each operation is defined by simple or composed gestures recognised by the iGesture framework [23]. In the case of insert operations or annotations, an Intelligent Character Recognition software [26] further processes the pen input and translates the handwritten information into a string to be added to the digital document. Every operation is composed of one or more gestures, optionally followed by some textual input. The different gesture-based operations are illustrated in Figure 12. Please note that different gestures can be used for the same operation.

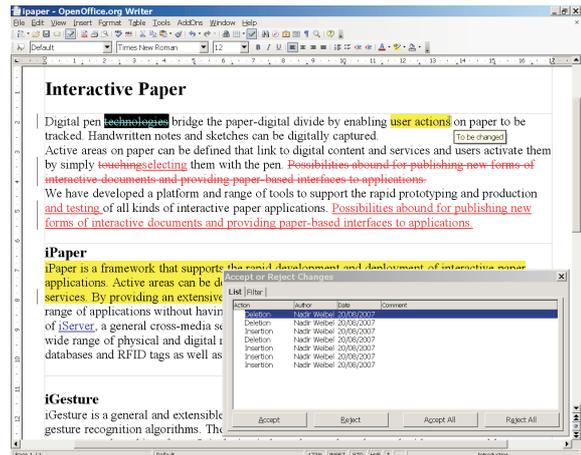
Depending on the gesture class, different granularity levels may be recognised and the system reacts in different ways.

- **Section:** **annotate** and **delete** are the two supported operations. The whole content of the section will be annotated or removed.
- **Graphics:** the **delete** operation which removes the graphics from a document is the only operation currently supported.
- **Table:** **annotate**, **delete** and **move** operations are supported. The annotation is inserted in the first cell of the table and, in the case of a deletion, only the content of the table is deleted, but not the table itself.
- **Text:** this category involves paragraphs, words and characters. All operations are supported.

Since users can make multiple corrections, it is important to ensure that the execution of an operation does not influence the position of succeeding operations within the digital document. Therefore, we first collect all operations with the digital pen and synchronise it with the OpenOffice source document. Collecting the operations might also be done in a mobile environment with the user on the move. In such a case, all information would be stored within the pen and the synchronisation would occur when users return to their computer. However, some sort of feedback would be useful to inform the user about the performed operations. Unfortunately, there is currently no way to provide feedback on the digital pens. This is a known issue and there have been solutions proposed to solve this problem [10]. In



(a) Corrections on paper



(b) Change tracking in OpenOffice

Figure 11: PaperProof

PaperProof, we currently only use the computer screen for feedback.

It may happen that a gesture is not recognised or that the written text is not detected correctly. For that reason, we provide an undo button which can be used to iteratively undo operations. As shown in Figure 11a, the synchronise and undo buttons are currently printed in the document header. As soon as the corrections are transferred to the system, PaperProof makes use of the approach outlined in Section 6 to retrieve the elements to be edited and execute the edit operations. Since we are using the change tracking functionality offered by OpenOffice, a user may still go through all edits and specify which to accept and reject.

Delete	 or 	
Replace	 or 	+ ICR
Insert	 or 	+ ICR
Move	 or  or 	+  or  or  + 
Free Annotation		ICR
Side Annotation	 or 	+ ICR
Two Point Annotation	 or  or 	+  or  or  + ICR

Figure 12: PaperProof gestures

Note that based on the OpenOffice change tracking functionality that supports different authors, our application could easily be extended into a collaborative proof-editing system. In this case, a document could be printed several times and each copy distributed to a different author. Existing digital pens provide unique IDs enabling the system to handle corrections from different reviewers.

## 8. IMPLEMENTATION

The implementation of the PaperProof application is based on the four main components, iPublish, iDoc, iPaper and iServer, that have been developed for general paper-digital integration and interaction. We will first briefly introduce those four components and then provide specific implementation details about PaperProof.

The *iPublish* component consists of a series of plug-ins defined for different kinds of documents. Depending on the type of document we are interested in (PDF, Microsoft Word, OpenOffice, etc.), iPublish allows specific plug-ins to be defined that either track structured elements from within an authoring tool or analyse existing paginated documents. The basic purpose of the iPublish layer is to identify both the physical and the structural information of the document. Plug-ins have already been defined for the automatic authoring and publishing of documents coming from a Content Management System [15] and for the semantic analysis of PDF documents [17]. During the development of PaperProof, a new iPublish plug-in for OpenOffice was defined based on the OpenOffice SDK [18] that allows programmatic access to all of the features offered by the OpenOffice authoring suite. By using the SDK API, we could get access to the structural information of the document stored within the document in a tree-based model and define the OpenOffice highlighters outlined in Section 5. Using the same approach, other plug-ins for a given authoring tool, such as a PaperProof plug-in for Microsoft Word, could be defined. The implementation of this specific iPublish plug-in might be based completely on the existing infrastructure. However, since the creation of an XPS file from a Microsoft Office document through the plug-in for XPS already provides all the structural information that our infrastructure needs, the highlighting phase would be simplified and only a specific snippet extractor for Microsoft Office needs to be implemented.

The *iDoc* framework is based on a mixed digital and physical model, which is able to store metadata about

both the digital and paper instances of a document [29]. This mixed model is based on two distinct parts representing metadata coming from logical structures, also referred to as digital documents, and paginated formats sometimes called physical documents. The idea outlined in Section 5 to have the possibility to refer to the logical representation of the objects at every level of granularity was developed according to the composite design pattern shown earlier in Figure 3 and is one of the building blocks of the model implemented within iDoc.

The *iServer* and *iPaper* components are responsible for linking paper to digital services [22]. During the printing process, all information required to identify the interactive paper documents as well as link definitions are published to the iServer database. The iPaper plug-in is then responsible for enabling access to those links by selecting specific active areas on a paper document. Each time a user points to an (x,y) position within an active area, the iPaper plug-in resolves the selected shape and its associated links will be activated. In order to resolve the correct shape, the iPaper plug-in needs three inputs: a document identifier, a page number and the (x,y) position within the page.

The definition of the mapping from paper back to OpenOffice and the implementation of PaperProof involved two major tasks: the implementation of an iPublish plug-in for OpenOffice and the design and implementation of an iDoc extension that uses XPS documents to retrieve elements within the original digital document. In the rest of this section, we provide more details about the PaperProof implementation.

After a new digital document has been created with OpenOffice, the iPublish plug-in enables the publishing of an interactive paper version of the document based on Anoto technology. The structure of the file is analysed and information about the highest granularity level is extracted. An XPS file is then generated and annotated and the document is ready to be edited on paper. In order to support this paper-based interaction, the information about the Anoto pattern used and the location of the OpenOffice document has to be published to the iPaper plug-in.

As soon as an area on the page is touched with a digital pen, a special operation buffer is initialised and the operations, recognised by the combination of iGesture and ICR as explained in Section 7, will be stored. The entire application logic is implemented as an *active component* within the iPaper framework. An active component is basically a piece of program code that is loaded at link activation time and becomes a handler for the information from the input device [22].

When all annotations and corrections have been collected, the user touches the *synchronize* button (see Figure 11a) which activates another active component to retrieve the corrections from the buffer and send them to the document mapper. In order to do that, PaperProof provides the **Corrections** class with the signature shown in Figure 13. The constructor of this class requires four parameters: a list of edit operations to be performed, the path and the version of the OpenOffice document to be edited and the path of the XPS file that contains the mixed digital-physical information.

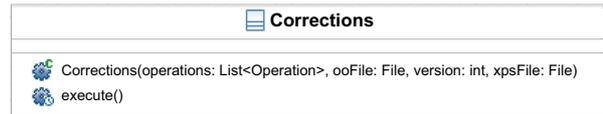


Figure 13: Corrections class

The **Corrections** class is the connection between the existing iServer/iPaper infrastructure, the iDoc framework and the PaperProof application. A schematic representation of the information flow is outlined in Figure 14. The `execute()` method iterates over the received edit operations and extracts the (x,y) position of the corrections from the digital pen. At this stage, the **XPSElementFinder** class extracts information about the selected printed elements from the XPS file which is then forwarded to the **AdapterXPSOO** class retrieving the corresponding digital OpenOffice elements.

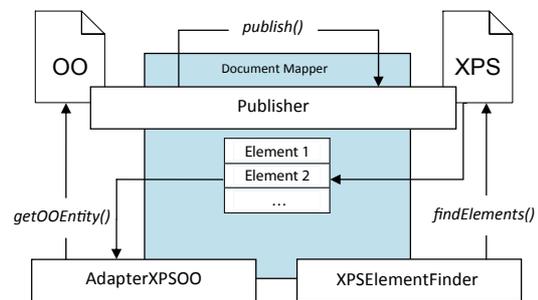


Figure 14: Information flow in PaperProof

After the corresponding digital elements have been retrieved, a **ChangeTracker** will transform the user operations into OpenOffice annotations and edits. As already discussed in Section 7, the changes to be applied in OpenOffice depend on the detected granularity level. For that reason, there exist four types of ChangeTrackers for sections, tables, graphics and text, respectively. Moreover, before executing any corrections, we first instantiate the ChangeTrackers needed for the execution of all the corrections. In the case of several authors, all their ChangeTrackers get instantiated at the same time and all the elements of the document that have to be corrected are properly referenced. Even if they were moved by a previous operation, the corresponding ChangeTrackers are still able to retrieve them. In this way, we ensure the safe execution of all corrections.

## 9. DISCUSSION

In Section 3, we presented the requirements for paper-digital proof-editing tools and highlighted some of the features that are missing in existing systems. After presenting and validating our solution, we now position it with respect to the original requirements.

An analysis of existing approaches shows that they differ significantly from the solution presented in this paper. In terms of paper-digital interaction, our proof-editing application seamlessly integrates paper and digital document versions in a similar way to ProofRite and

paper-based annotations are automatically transferred to the original digital document. However, instead of simply integrating handwritten annotations into the digital document, PaperProof interprets them and applies the edits to the digital document instance.

In digital-only solutions as well as existing paper-digital approaches, captured annotations will reflow if the digital copy is edited. However, the notes are still bound to relative positions within the digital document instead of referring to structural elements within the document. ProofRite refers to the position captured from paper, while digital-only systems retrieve the position returned by the stylus used on a display. Due to the lack of a binding between the structural elements of a document on paper and those in digital form, existing systems do not support the automatic integration of edits and only provide visual clues. Instead they simply copy the annotations into the digital document and still require editing operations to be performed manually.

In contrast, annotations and editing operations are interpreted and executed by PaperProof. Our system is unique in analysing paper-based edits and transforming them into operations and textual annotations based on gesture recognition and ICR technologies. To the best of our knowledge, our system is the only paper-based editing solution that also exploits change tracking functionality offered by digital authoring tools.

The automatic publishing of interactive paper documents is also supported by PaperProof which makes use of the iDoc Virtual Printer [16] to support the production of an augmented document based on Anoto technology. The virtual printer can be selected from the list of available devices and the digital document is automatically analysed and augmented with Anoto pattern. The user does not have to perform any additional steps and can start the proof-editing session as soon as the document is retrieved from the printer.

PaperProof also reveals some issues to be solved in terms of usability. It is often difficult to understand a user's intentions by using only pen-based gestures. The PaperProof gestures have been selected in a way that should feel natural to the end user. However, we plan to do some user studies in order to evaluate the usability of the paper-digital user interface.

The automatic granularity check presented in Section 6 enables a much smoother interaction with the system, without the user having to explicitly select the granularity level. However, dealing with precise gestures may lead to a lack of accuracy on the user side, which may easily cause unexpected results. For example, if the pen accidentally touches the next word while deleting a word, that would also be deleted. Since the user intention is not known a priori, the system should automatically select the best solution. What does it mean, for example, if a user crosses out all the characters in a word except the last one? Is there only a lack in precision or should the last character really not be removed? Our algorithm for the automatic granularity detection works fine but the analysis of user intention is still a source of potential misinterpretations. User studies will also be required to determine the best way to handle these issues.

While the retrieval of digital elements based on the selection of the corresponding element on paper works well, there are still some problems in terms of performance. This is probably due to the current implementation which uses the XPS file as the repository for elements. This is costly in terms of performance since parsing an XML file and searching for an element is a rather slow operation. Moving to the document database provided by the iDoc framework should lead to faster element retrieval.

The lookup of digital PaperProof elements is based on the relative position of an element with respect to its parent element. This is a generic approach which could also be used in the development of different plug-ins, for example a PaperProof authoring tool for Microsoft Word. A future Microsoft Word plug-in might be completely based on the existing infrastructure. The implementation of the iPublish plug-in would be straightforward since the XPS documents created from a Microsoft Word document already contain the semantic information required by our infrastructure. Therefore, the only parts that would have to be changed are the PaperProof application itself and the iDoc extension with the implementation of a simple snippet extractor adapted to the semantic information stored within the XPS files generated by Microsoft Word.

From this brief analysis, we see how our PaperProof application and the related technologies go a step further in the definition of an effective paper-digital proof-editing system and provide a solution for some of the open issues presented in Section 3. The PaperProof application further demonstrates the feasibility of a bidirectional paper-digital mapping.

## 10. CONCLUSIONS

We have presented a novel approach for capturing the structural model of a digital document during the printing process in order to maintain a logical, bidirectional mapping between digital and paper instances of a document. Our approach has been validated by PaperProof, a paper-digital application for document proof-editing that, not only enables comments to be captured as annotations, but also provides digital editing functionality based on the interpretation of handwritten gesture-based commands.

We plan to extend PaperProof in order to fully support multiple simultaneous reviews of the same document. This requires the definition of a version model which has to be shared between the paper and digital document instances. We also plan to carry out user studies and investigate various issues that may affect system usability, including feedback mechanisms and the gesture-based interaction design. Last but not least, we aim to develop an alternative PaperProof implementation based on Microsoft Word.

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# Tabletop Interfaces for Remote Document Review Meetings

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## ABSTRACT

We consider the problem of remote review meetings, in which geographically-separated colleagues review text documents. We propose remote tabletop interfaces as an approach to addressing this problem and show that the necessary underlying technology has now progressed sufficiently to allow exploration of this new research area. We present a novel remote tabletop interface that we have created to investigate this area, and discuss our design in the context of prior work.

## 1. INTRODUCTION

Many knowledge workers spend a significant proportion of their time discussing and revising draft documents with their colleagues. These document review meetings have been well-studied in the literature, and are predominantly carried out while sat at meeting tables and using paper documents [8]. As an example, consider two co-authors of an academic paper, discussing each other's draft contributions.

Starting with Freeman and Wellner's DoubleDigitalDesk [15, 16, 17], researchers have turned their attention to the problem of *remote document review meetings*, i.e. document review meetings in which the participants are geographically-separated. These research projects seat each participant at his or her own table and then use video cameras to show each participant an image of their remote partner's table. Thus both participants can see each other's paper documents, gestures and actions during the discussion.

However, these systems can be problematic because a given paper document is only ever tangible for one of the collaborators. Their partner sees merely a remote image of it, cannot rearrange it on the table, turn pages or make annotations and, depending on the system, may not be able to read small text.

Recently, several researchers in the tabletop community have investigated the possibility of linking two large interactive

horizontal displays together to support remote collaboration [1, 2, 5, 10, 13]. As shown in Figure 1, this creates a shared workspace containing "virtual objects" that are not tangible to either collaborator. These remote tabletop interfaces are largely unexplored.

In this short paper, we propose remote tabletop interfaces as an alternative to the DoubleDigitalDesk approach for supporting remote document review meetings. We begin by contrasting the two approaches (Section 2). We then present our recent work on high-resolution remote tabletops as a suitable technology platform from which to begin exploration, and describe prototype interfaces (Section 3). Finally, we draw on previous studies of tabletop collaboration and document review meetings to discuss design issues that arise in such systems (Section 4).

## 2. REMOTE TANGIBLE AND REMOTE TABLETOP INTERFACES

DoubleDigitalDesk [15, 16, 17], Tele-graffiti [9], LivePaper [6], Agora [4] and various commercial videoconference systems all address the problem of remote review meetings using what we shall call a *remote tangible* approach. A video camera mounted above each participant's table captures images of the paper documents on the table. These images are presented to the remote partner, either on a screen or projected onto the table in front of them. The participant with the tangible paper document is able to annotate it using a conventional pen, turn the pages and rearrange the document on the desk, whereas their partner sees merely an image of the document and can do none of these things. Both participants can see each other's hand gestures in the context of the document. Depending on the resolution of the camera and display, and the size of the text, the remote participant may or may not be able to see the text sufficiently legibly to read it. A similar approach has been adopted elsewhere to support remote collaboration over physical assembly tasks [3] and board games [18].

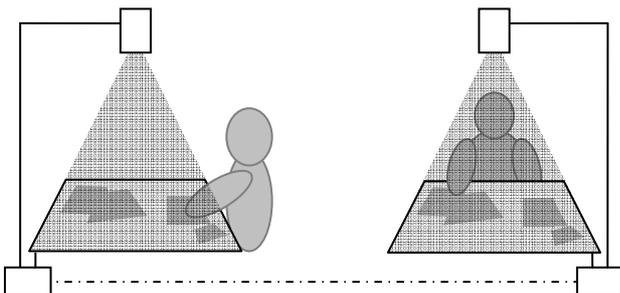


Figure 1: Remote tabletop interface.



Figure 2: Tiled multi-projector display.

By contrast, in systems using a *remote tabletop interfaces* approach [1, 2, 5, 10, 13], the objects are tangible to neither collaborator. Each collaborator sits at his or her own large interactive horizontal display. The two displays are then linked together, perhaps via the Internet, to provide a shared workspace for remote collaboration. The displays show virtual objects, such as virtual pages of text, that collaborators can move, reorient, annotate and otherwise manipulate using either their bare hands or styluses, depending on the technology. The displays also show the collaborators each other's arm gestures as shadows overlaid on the display.

Tabletop interfaces are a promising area of investigation. They support some of the affordances important for co-located document review meetings, such as a large horizontal workspace on which documents can be compared side-by-side [8]. For design tasks they have also been shown to support some of the coordination mechanisms observed in collaboration around conventional physical tables, such as fluid transitioning between coupling styles [11]. *Escritoire* [1] and the very recent *C-Slate* work [2] are both remote tabletop systems for document review tasks. However, these projects focus on the supporting technology, and both remote tabletop interfaces and remote document review meetings on them are still relatively under-explored.

### 3. OUR SYSTEM

The reasons for this gap in the research are two-fold. Firstly, it is necessary to display the documents at a sufficiently small size that they can be passed around the table between collaborators, grouped into piles and compared side by side. This requires the ability to display small text legibly on a tabletop display but, until recently, the resolution of tabletop displays used in research labs was too low to support this. Secondly, it is technically quite challenging to create remote display systems that support tabletop interaction techniques and a high display resolution while remaining responsive, because the combination of requirements was, until recently not addressed by research tools.

We have recently addressed these issues by creating the T3 toolkit [14], a software library that allows researchers to easily create high-resolution tabletop interfaces by tiling multiple projectors together, and to create remote high-resolution tabletop interfaces, and to rapidly create prototype interfaces for such systems. We have created two high-resolution tabletop displays, each using between 4 and 6 projectors in a tiled array to create a display of area 0.5m<sup>2</sup> and resolution 60dpi, capable of displaying legible text at font size 12pt (Figure 2). Such displays are, of course, too costly and complex for wide-scale deployment, but allow us to prototype ideas that may eventually be available to the mass market using the cheap, thin, flexible “e-paper” displays currently under development.

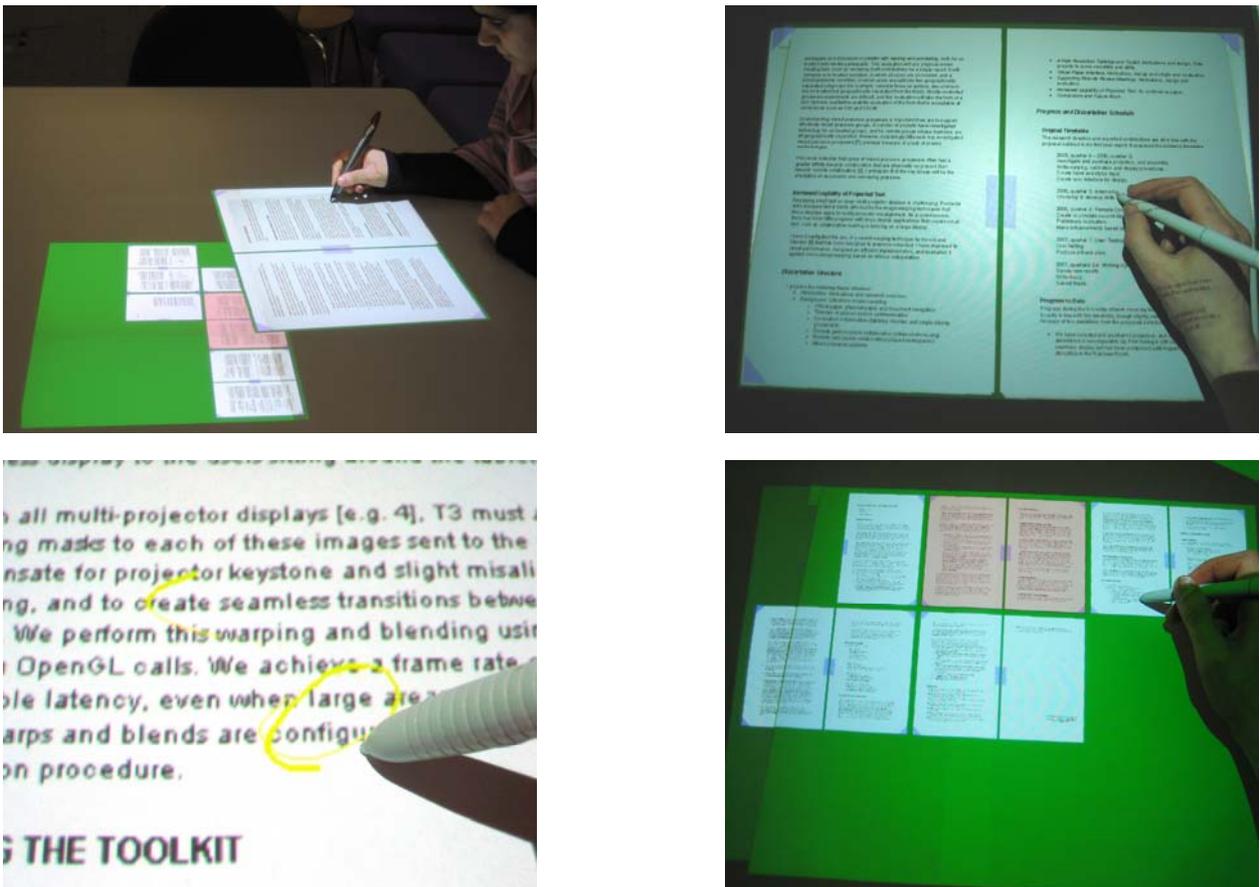


Figure 3: Documents appear as virtual pages of text on the tabletop (top left). Two pages are visible at once (top right). Text appears legible at size 12pt, and telepointers allow remote gesturing (bottom left). Thumbnails allow browsing (bottom right).

The projectors generate sufficiently little heat and noise as to not distract collaborators.

Using T3 we have created three prototype interfaces. The first interface (Figure 3) allows multi-page text documents to appear as virtual pages of text on the tabletop, showing two pages at once, rather like an open book. Text appears legible at size 12pt, and collaborators can use styluses to annotate, navigate, move and reorient multiple documents in the workspace. Using marked control points on the page, collaborators can navigate either by “turning” from one page to the next, or switching to a thumbnail view. Collaborators can gesture to each other using bright telepointer traces that follow the stylus nib, and we are currently completing an extension to allow gesture using translucent arm shadows.

Our second and third interfaces are the first steps in an investigation of tabletop collaboration over web pages (Figure 4). Although web page tasks are likely to be somewhat different from remote document review meetings, the interfaces offer an opportunity to explore interaction with multiple documents that are structured both spatially (in terms of their links to each other) and also temporally (with respect to their position in the web browser history tree or stack). The basic interface allows pages to be freely reoriented and repositioned on the tabletop by the collaborators, whereas the history tree interface determines the location and size of the page according to the time at which it appeared and the page from which it was opened.

#### 4. DISCUSSION

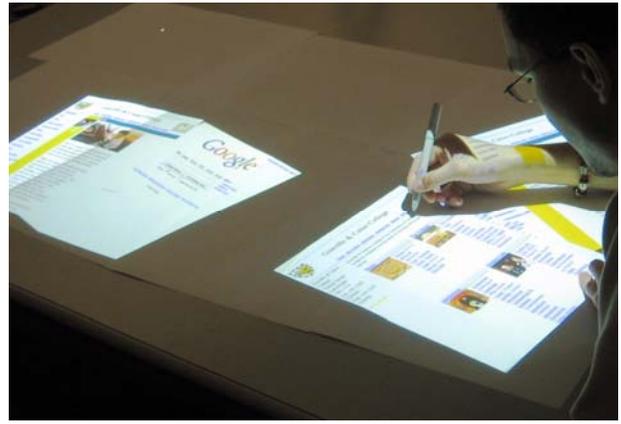
Our investigation of remote tabletop interfaces to support remote document review meetings is still at an early stage, and future work will involve a field study. Nevertheless, even in this early work we have identified several issues that must be considered in the design of such systems.

In their investigation of paper documents, Sellen and Harper [8] emphasise the importance of the affordances of paper for reading and reviewing:

- Ease and flexibility of navigation.
- Ease and richness of annotation.
- Ability to cross-reference and compare multiple documents.
- Visibility of actions to colleagues.
- Ease of interweaving of reading and writing.
- Ability to annotate or read, and discuss in parallel.

These were most influential when designing our interface, and led us to a design based on replicating paper rather than anything more radical. Of course, because of the constraints of the system and the approach, we would not claim that our interface affords these nearly as well as paper does. However, surpassing paper was not our aim in this project; rather, we set out to create an effective interface for remote collaboration in document review meetings.

In reviewing prior work, we contrasted the approaches of remote tangible systems and remote tabletop systems. We believe that the two approaches present a tradeoff between symmetry and effectiveness in the extent to which they afford the properties identified above. A remote tangible system offers one of the participants the ability to interact with a document in a tangible, unconstrained manner, affording effective bimanual actions for navigating and arranging documents, and rich annotations, while their ability to read and write is not limited



**Figure 4: Basic web-browsing interface (top) and history tree (bottom).**

by a display resolution. However, the other participant cannot interact at all, and their ability even to read the document is likely to be severely constrained by the camera resolution and camera noise. By contrast, remote tabletop systems offer symmetric but less effective, more constrained interaction. Bimanual actions, fine-grained annotations and display resolution are likely to be limited by the capabilities of the system for both participants.

One exception to this tradeoff is that, because of the constraints of today’s technology, remote tangible systems tend to offer small disjoint workspaces, and so our remote tabletop system may well better support the ability to cross-reference and compare multiple documents.

It is also interesting to speculate as to whether, even in a co-located document review meeting, each collaborator asserts a strong ownership over the documents that he or she has brought to the meeting, leading the collaborators to naturally partition their actions between the documents in such a way that the asymmetric access of remote tangible systems does not present them with a problem. We are not aware of any studies of this effect, and we shall investigate it in the field study.

In designing the interface we have adopted and adapted several design principles from the tabletop community, such as small virtual objects on a large display, lightweight mechanisms for moving and reorienting, mimicking tangible objects with projected light, and aiming to afford the styles of collaboration observed around conventional physical tables. However, these principles were derived largely from observations of design tasks [e.g. 12] rather than document review tasks, and have

been validated in studies of co-located tabletop collaboration rather than remote collaboration. The extent that they can be applied to document review tasks and to remote collaboration remains unclear and we shall investigate this in the field study.

Finally, we observe that remote tabletop interfaces allow both collaborators to sit at exactly the same location at the edge of the “virtual table”, a situation which, in co-located tabletop interaction, is not physically possible unless the collaborators sit on each other’s knees. Seating arrangements in co-located tabletop collaboration are governed by proxemics and the extent to which the task demands that the collaborators share a common perspective of the workspace [7]. It is unclear as to how remote collaborators will prefer to arrange themselves, and again we shall investigate this in the field study.

## 5. CONCLUSIONS

In this short paper, we discussed remote tabletop interfaces as an alternative to the remote tangible approach for remote document review meetings. We showed that, using the T3 library for high-resolution remote tabletops, it is now possible to begin exploration this area, and we presented three interfaces that we have created rapidly using T3. Drawing on our early experiences in designing and implementing these interfaces we discussed issues that must be considered when designing such systems.

## 6. ACKNOWLEDGEMENTS

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# The Paperoles Project: An analysis of paper use by music composers

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## ABSTRACT

Technologies such as Anoto offer a novel approach to supporting the creative design process, by integrating paper with on-line tools. However, creating successful 'augmented paper' applications requires a detailed understanding of the existing and potential roles of both paper and computers. This paper describes our study of contemporary music composers, who are highly skilled users of both. We challenge common assumptions, particularly that paper's key value lies in its flexibility and describe our early prototypes of augmented music scores. We conclude with implications for the design of augmented paper applications that support creative work.

## Author Keywords

Augmented Paper, Composers, Participatory design, Musicians, Music scores

## ACM Classification Keywords

H.1.2 [User/Machine Systems]: Human Factors, H.5.2 [User Interfaces]: Evaluation/methodology, Theory and methods, Prototyping, User-centred design.

## INTRODUCTION

We have long been interested in the role of paper in human activity, ranging from biologists' lab notebooks, air traffic control flight strips or engineering drawings (Mackay, 1998). Each project focused on the balance that must be maintained by people who have excellent reasons for using both paper and electronic tools: each medium has its advantages and its disadvantages and we were interested in studying how to make optimal use of the two media together.

This study is somewhat different. Our user population consists of professional musicians, who use both paper and computers to compose music. Here, our goal is not to increase efficiency or accuracy, per se, but rather to support a highly individual creative process. We began by interviewing professional musicians at IRCAM, in Paris, and observing them at work. This paper describes the results of those interviews, including some counter-intuitive conclusions with respect to their use of paper. We conclude with a design scenario that illustrates how one would take these findings into account when designing an Anoto-style application, in order to enhance the musician's use of both paper and electronic media when creating music.

## STUDY: INTERVIEWS OF COMPOSERS

IRCAM is a world-renowned centre for electronic and contemporary music, created in the 1970's by Pierre Boulez.

Composers and musicians come from all over the world either to compose new works or to collaborate with other musicians on new projects. Composers pose an intriguing user interface problem: how can they use the computer as tool, but still feel as though they are creating art? The problem is not to increase efficiency, but rather to enhance reflection and increase expressiveness. The composers clearly do not want a system that automatically composes for them. Instead, they need tools that help while leaving them the masters of the creative process.

We interviewed 12 composers and musical assistants at IRCAM. The composers were either proficient computer users themselves or else had extensive access to music assistants who can program for them. Most music assistants were computer scientists with additional training in musical. We interviewed both individual composers and composer-assistant pairs, in their offices or the laboratories where they composed music, to better understand the process by which they create new music. We also met with the *Analyses des Pratiques Musicales* team at IRCAM to discuss their longitudinal study with a single composer (P. Leroux) and how he used paper in the process [Donin 2006].

## RESULTS

Our analysis showed that, despite access to the latest computer-music tools, these composers continue to use paper to edit, annotate and link their musical scores. Despite their technical proficiency, most composers continue to use paper documents as a fundamental part of the composition process. They are dissatisfied with the lack of connection between their off-line scores and other annotations and the on-line software that generates the resulting music. Letondal et al. (2007) report in more detail about the study: this paper concentrates on two sets of results. First, what is the chronology of paper use: When do composers use paper and the computer? Second, when given a choice, how do they choose between the two?

### Chronology of paper and computer use

Why haven't composers of electronic music shifted to an entirely computer-based composition process? It is due neither to fear of computers nor to particular problems with the user interface (especially since most of their tools are designed by and for musicians). Instead, like people in other fields, (Sellen and Harper, 2003), composers choose the medium that is best suited to the purpose at hand.

We summarize the varying roles of paper and computer throughout the composition progress in Fig. 1. Composition progresses from the initial creative stage to the final piece, with much iterative development in between. Throughout this process, the artefacts change, from quick sketches in the beginning, through progressive experiments in the middle, to the final composition at the end. The characteristics that composers value in paper and the computer also change. In the beginning, most composers prefer paper because of the freedom of expression it offers. In the interim stages, they prefer a mix of paper and computer, valuing both ease of modification and power of expression. At the end of the process, most prefer

paper because it acts as a reference artefact and permanent record of the work. Most of the augmented paper literature emphasizes paper's flexibility as a key value; we argue that its role as a permanent record is equally important, with major implications for the design of these applications.

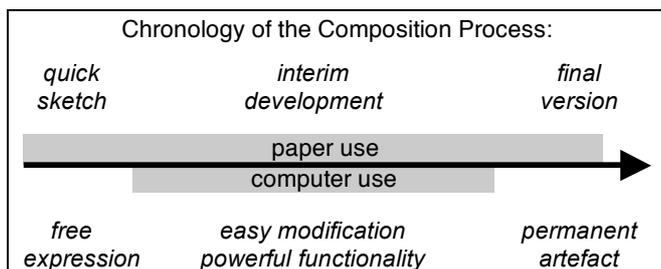


Figure 1: Paper is used from beginning to end of the composition process. Computer and paper are used together during the interim development phase.

In the early idea-generation stage, composers use paper because it is flexible, easy to transport and less cumbersome than a mouse or a stylus on a graphics tablet. Most importantly, paper enables great freedom of expression: the composer is not restricted to the particular input structure of a particular computer program, but can use any combination of drawing and text, enabling free expression of artistic ideas. We saw numerous innovative examples of using paper to sketch or capture initial ideas. One composer created a diagram to describe the structure of a symphony (Fig. 2a) and while another drew magic squares to determine the phrasing of his composition (Fig. 2b).

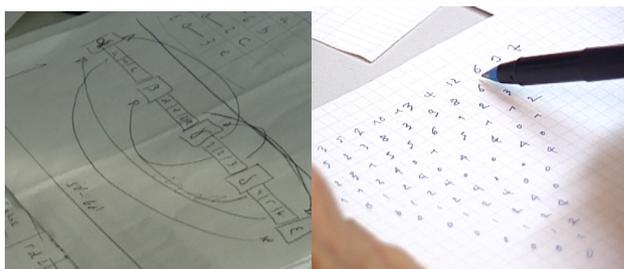


Fig. 2a: Organising the components of a symphony  
2b: Using a magic square to denote phrasing

Composers also annotate hand-written scores. In Fig. 3, the composer has added numbers under each instrument part to indicate loudspeaker assignments to give a spatialisation effect.

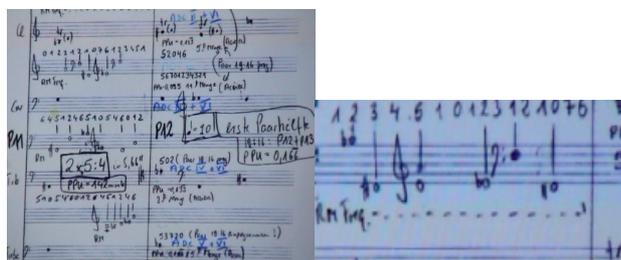


Fig. 3: Annotations to a hand-written score

At the other end of the composition process, the choice of paper has less to do with the flexibility of input, but rather its status as an archival object. One composer reported that he even paid someone to hand rewrite his scores, from the 'final' version on the computer, so as to create the true, 'original manuscript'.

### Choosing between paper and computer

At the beginning and end of the composition process, composers prefer paper. However, in the middle, composers use both paper

and the computer, shifting back and forth to take advantage of the characteristics of each. They use paper when they need freedom of expression, and the computer when they need to calculate algorithms or generate new musical sounds.

*Non-conflict situations:* In many cases, this poses no conflict. For example, in Fig. 4a, the composer goes back and forth from the printed score to various musical materials such as a program, a drawing (Fig. 4b), a text document containing a poem used as seminal data to build sounds, a rhythm series for the piece, etc. The printed score can be browsed rapidly, examined and compared to an electronic document displayed on the screen. This composer uses paper folders, containing various sheets of paper, sometimes cut from larger sheets, in order to keep track of the structure of his piece.

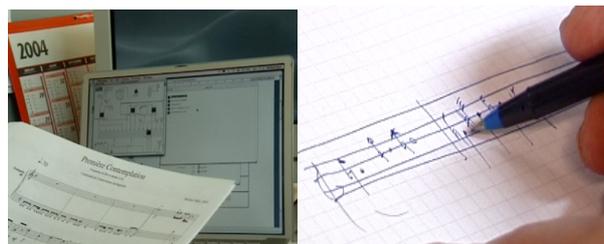


Fig. 4a: Navigating between paper score & on-line files  
4b: Extended musical notations for 1/4 and 1/8 tones

Fig. 5 illustrates a more complex interaction between the two forms. The composer has drawn an arbitrary s-curve on paper to define a particular sound segmentation. After annotating this acoustic shape, he explained that he would now have to input it again to a dedicated software tool that calculates the spectral envelope. Although this particular composer happens to be a skilled LISP programmer, he does not use either mouse or pen-input to draw such curves. He prefers to sketch curves on paper first because it is easier and more direct, and then use a scanned and/or re-implemented version on the computer.

Rather than creating one specific program for each creative idea, paper enables these composer to spontaneously generate any idea that occurs. Then, these ideas are translated into music, perhaps via paper score for human musicians or as input to a computer music program.

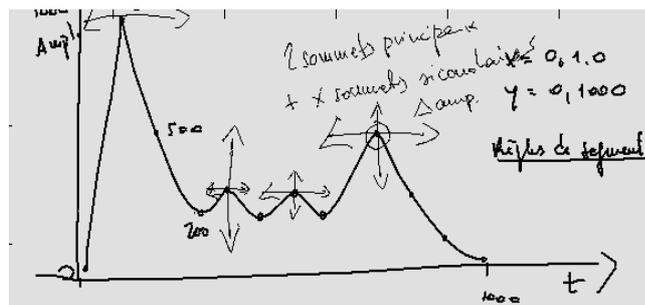


Figure 5: Hand-written drawing of an acoustic envelope. By recording of the strokes coordinates, the drawing can also be displayed on the computer screen.

*Conflict situations:* Composers sometimes face a conflict, because neither medium suffices by itself, but the media do not work well together and it is difficult to decide between them. Time is not the issue: when asked whether paper or computers were faster, one said that, in the end, neither was faster and another commented that the computer allowed him to "lose time in order to gain space". In classical music, instruments provided composers with the opportunity the explore and interact with the music as it was being composed. In electronic music, computers serve the same function, allowing composers to create new instruments and sounds and interactively explore a musical

space. But the preferred medium for imagination and writing remains paper, *because it is slow and static*. We observed that electronic editors for writing music, such as Finale, are used mostly for the non-inventive part of the composition or for traditional composers.

Composers must decide which medium to use for the final representation of the score. In classical music, each work is transformed into the “original score”, on paper. This serves as an authoritative reference for the piece, which can then be archived and copied. But with electronic music, the choice of the final format is more complex. For example, in Fig. 6, the composer has pushed his software to the limits by including graphical notations that indicate particular sounds the choir must make, in addition to standard notes. These symbols must be defined separately and linked to the associated sounds, which are stored on the computer. So the “original score” is archived in a mixed paper and electronic form.

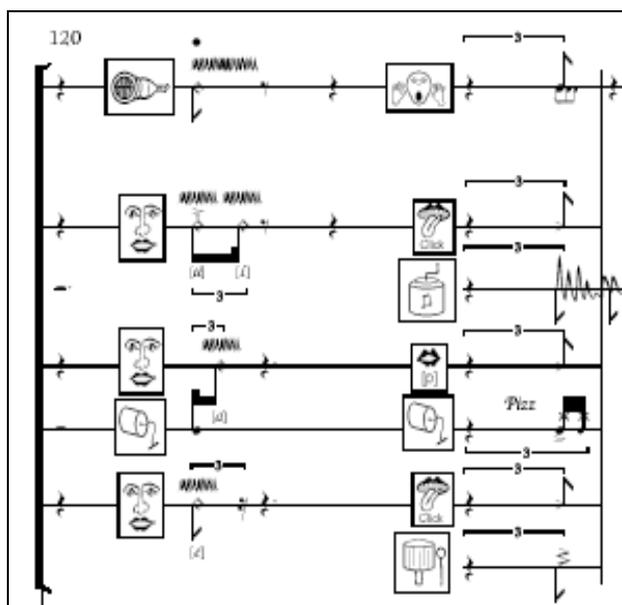


Fig. 6: Score with added symbols to show actions to be performed by the choir.

Similarly, Fig. 7 shows a hand-written score with links to a variety of electronic documents and statements that trigger particular computer programs while the piece is being played. This hand-written paper score serves as the key reference point, with links to the computer, but the final work is fundamentally located both on-line and on paper.

## DISCUSSION

We see that paper is the preferred medium at the two extremes of the creation process. In the beginning, paper is excellent for quick sketches that express ideas as directly as possible: the composer does not have to fit the ideas to the particular software at hand, but rather records whatever makes most sense with respect to the idea. The composer can experiment freely with different ways of expressing the idea and stay focused on the idea itself. At the other end of the spectrum, paper acts as the final, archival form of the finished score, except in particular cases in which the paper score is linked to on-line files to create a mixed archival document. In the interim design phase, composers shift back and forth between paper and computer, choosing the representation that makes most sense for the task at hand. Sometimes this works well, when paper and the computer are complementary; sometimes this causes conflicts that are difficult to resolve.

## DESIGN SCENARIO

We find that analyzing qualitative data into a design scenario is a useful technique for extracting the key concepts that emerge from the data and transforming them into a form that guides our design. By situating our ideas in the context of real use, we can also more easily obtain feedback and additional ideas from composers. The following design scenario describes a composer using *Paperoles*, a technology probe (Hutchinson et al., 2003) that uses Anoto technology to integrate paper and computer-based composition. We have created video prototypes of this and related design scenarios and are currently implementing the related software.

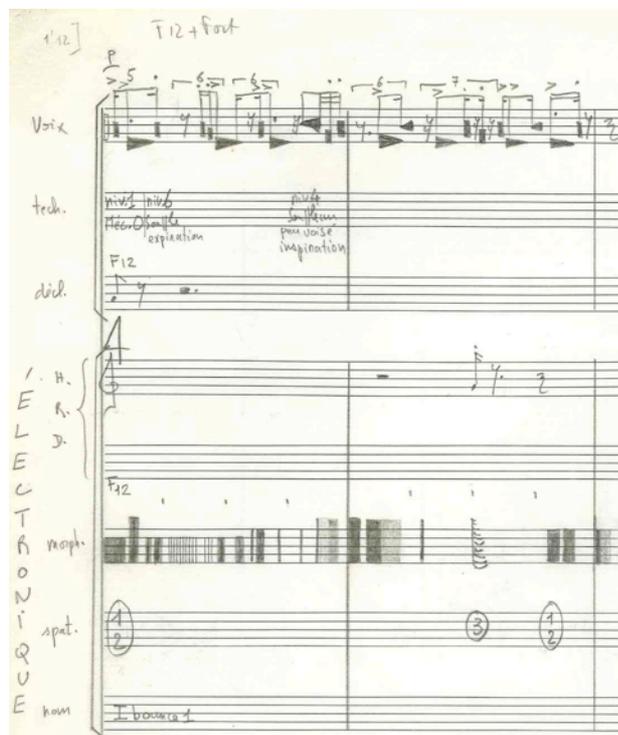


Fig. 7: The word Electronique is written vertically, with links to other computer programs to be played in addition to the more traditional score to the right.

### Interacting with mixed scores

Pierre is writing a new symphony, inspired by multiple sources: He translated a poem by Verlaine into Morse code and used this as the initial pattern for the different rhythms in the piece and he selected the different timbres, based on models of musical instruments and voice. He uses a variety of different computer tools to support the composition process, including the popular OpenMusic system, as well as MAX/MSP and AudioSculpt. When he opens his composition on the screen, he sees hypertext links to different zones corresponding to the appropriate software. When he interacts with a particular page of the score printed on Anoto paper, he can open the related software directly, following the same set of links.

Pierre likes to wear noise-reduction headphones and read the most recent version of his score, printed on paper, on the train going home. He hears the music in his head and makes a number of changes, modifying notes and deleting several chords. When he arrives home, he marks the “send” button (printed in the bottom corner of his score), which sends the revisions to his computer via Bluetooth. The changes are incorporated when he next opens OpenMusic. Pierre uses the history function to compare them to the previous version, moving backwards in time. Each set of editing changes is highlighted and marked with the date and time. Pierre can add additional annotations and

notes, either on-line or on paper, depending upon which is most convenient at the time.

Like many contemporary music composers, Pierre creates new sounds for each individual piece. These sounds cannot be represented by traditional notes on a score, and require new symbols that define how to play the new sounds. Pierre sketches various ideas for different notations to represent these sounds and then marks his favorite on the printed score. His music assistant, George, has written a custom-made program to help Pierre express his ideas for the new composition. Pierre communicates with George by sending ideas for different notations via an annotation layer that sits on top of the relevant section of the particular version of the piece. Pierre decides to create a new sound by associating it with a particular frequency spectrum. He sketches several possibilities on sheets of paper, selects one, and creates an interactive annotation on the paper score with the appropriate information. When George later looks at the score on-line, he sees the modified notes highlighted, with a pop-up note that includes Pierre's explanation of the idea, a sketch of a symbol to represent it, and the sketch of the frequency spectrum (Fig.8). George transfers the sketch to a separate program, where he converts the curve into a playable algorithm, and creates a 'patch' that links the symbol and the spectrum to the original score. (This is an example of participatory programming (Letondal & Mackay, 2004).

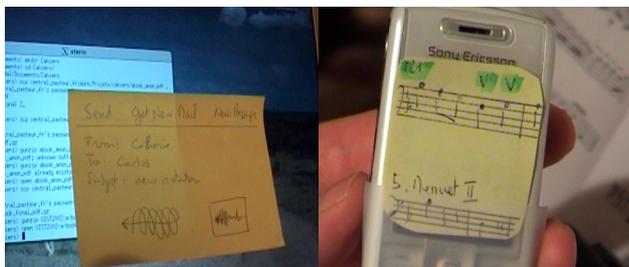


Fig. 8a : Videoprototype showing the annotation  
Fig. 8b: Message about bowing sent to violinist's PDAs

Pierre's composition is intended as a mixed piece, with human musicians and the computer playing together. Pierre inserts 'activate' commands into the paper score that Leonard, the 'chef de pupitre', uses to control when the computer plays. During rehearsals Leonard also makes changes to certain passages and communicates them to the musicians. These changes are captured on-line as well, and retained in the subsequent version of the score. Fig. 8b shows the changes in bowing instructions, with the affected notes highlighted in green and sent to the violinists, via PDAs located on their music stands.

## CONCLUSIONS AND FUTURE WORK

Our studies of composers demonstrates the important role that paper continues to play in the creative process, even when composers are adept computer users. Paper remains the optimal choice at the two extremes of the creative process: sketching initial ideas for the first time and creating an archival record of the finished work. However, some compositions require both paper and computer, which is not easily managed with current technology. Between these two extremes, composers mix paper and computers in a variety of ways, influenced by the particular input/output characteristics of each.

We are currently exploring the use of Anoto technology to expand the options available to composers. We are implementing a technology probe, called Paperoles, to address the issues identified in the design scenario and are continuing to work with IRCAM composers to further explore this design space. Our goal is to create a system that supports the cycle of 'sketch – interact on the computer – print – annotate on paper –

interact on the computer' in a more fluid and accessible way. This will allow composers seeking to add innovative notations to traditional music scores, a common theme in contemporary music, and provide a framework in which paper, printouts and files can be linked together and support the process of co-adaptation (Mackay, 2000) in which users are encouraged to adapt technology to meet their own unique needs.

## ACKNOWLEDGMENTS

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# Augmented Paper Applications: Initial User Tests Of A Wireless Pattern Reader

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## ABSTRACT

A handheld pattern reader has been developed to read low visibility conductive patterns on paper. The patterns are formed by masking conductive paper with a non-conductive, printed lacquer. The reader was developed as part of an EU-funded project investigating methods of augmenting paper. Data read from the patterns was used to trigger events in the digital domain. Usability tests were undertaken to investigate the performance of the prototype. Results showed that at this stage of development there was significant variation in performance of the prototype from user to user. Further work is being undertaken to determine the causes of this variability.

## General Terms

Algorithms, Measurement, Documentation, Performance, Design, Reliability, Experimentation, Human Factors, Standardization, Theory, Verification.

## Keywords

Digitally Augmented Paper, Wireless Pattern Reader.

## 1. INTRODUCTION

Paper continues to be a pervasive resource throughout society. Reasons for this have been reported and include paper's mobility, portability and its facilitation of mutual access and collaboration [1]. The concept of invisible, or at least non-obtrusive, patterns as information carriers for printed documents has also been reported [2].

A review of previous work in developing relationships between digital content and paper can be found in 'The Disappearing Computer' [3].

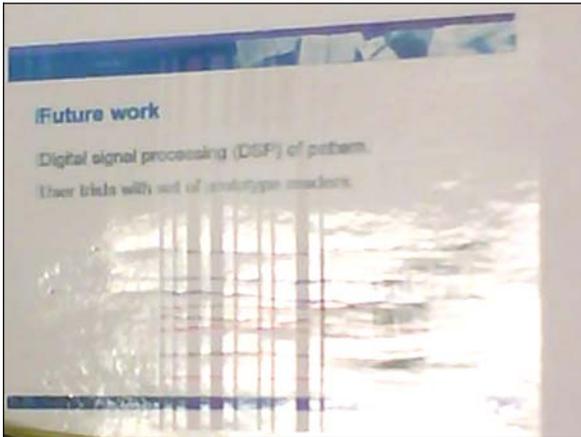
Developments in interaction between traditional and new media allow for the versatility of paper to be maintained whilst exploiting the advantages of digital media. The PaperWorks project aims to integrate the use of paper and digital applications in a variety of ways, one of which was the development of a wireless pattern reader. The conductive-pattern reader was intended as a very low-cost item; the conductive pattern was anticipated to be mass-manufactured as part of a printed document, without specialist requirements. The costs of printing and media production were beyond the scope of this investigation, but the conductive patterns on paper are produced using established printing and paper-making materials and processing.

The solution is inherently low-cost, as opposed to optically-based systems with high-cost electronics and processing elements. The hardware approach was taken as a result of interest in the use of conductive inks on paper. Such inks have been used to create electronic circuits and discrete components. In the same way as magnetic inks were used for 'computer print' in Magnetic Ink Character Recognition (MICR) financial systems (eg. cheques), the desire was to embed information digitally in/on paper, by a low-cost method, to add to its functionality.

The wireless pattern reader, under development as part of this project, makes contact with conductive paper, reads a conductive pattern and sends data to a software application. The application used for this testing is called PaperPoint, developed by Dr Beat Signer, Prof Moira Norrie and Nadir Weibel, at ETH Zurich. It is an application that links a pointing device to PowerPoint.

The paper used for the PaperPoint demonstration is a printed PowerPoint handout, coated with a conductive layer developed by ArjoWiggins, and overlaid with a lacquer, printed by Acreo AB. The insulating lacquer defines printed patterns on the conductive surface, masking where the pattern is. The patterns are placed over an image of each PowerPoint hand-out slide, with additional patterns for navigation; forward, back, start and end. The user simply has to swipe the relevant slide or

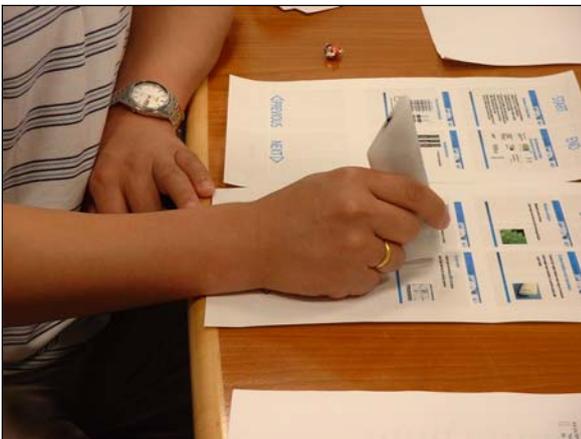
navigation icon to guide the presentation to the appropriate point.



**Figure 1. Image of a handout slide, showing lacquer-masked pattern.**

A user test was performed that looked at the advantages and disadvantages of the prototype. A slide sorting task was selected as the problem domain. The conventional way of controlling slide sorting is with a mouse, and so this was chosen as the comparable technology.

With the resulting findings, improvements are planned for the design of the reader, with an aim to make it more intuitive, effective, efficient, easy to learn how to use, comfortable, and acceptable. The overall aim is to develop an ergonomic reader that is as inclusive as possible.



**Figure 2. Pattern reader used on PaperPoint printout.**

## 2. SUMMARY

Eight people took part in the tests conducted over two days. On the first day of testing there was an average success rate of 51%. This dropped to an average success rate of 13% on the second day. There was a total of 819 swipes across the patterns. A wide range of success was seen from user to user, varying from 0% to 96% success. Further work is necessary to determine the source of this variability.

## 3. DESCRIPTION OF THE TEST

The usability test was carried out on a sample user group. Data was gathered on their use of swipes to control a PowerPoint presentation.

A control was set up to compare the use of the reader to the more usual way of controlling a PowerPoint presentation with a mouse or the keyboard.

### 3.1 Apparatus

The user test required the prototype reader, a PowerPoint printout with low visibility barcodes, a Bluetooth-enabled laptop installed with the PaperPoint application and PowerPoint, and a desk to rest on. A camera was also needed to photograph the participants' grip of the reader and a stopwatch to record the length of time each part of the test took.

Due to the low visibility of the conductive pattern, the barcodes were stretched vertically, to fill the image boxes of the slide hand-out. This facilitated the location of the pattern, as it was contained within the defined image area of each slide box.

### 3.2 Procedure

The tester manually recorded the success of each swipe. The results were logged as "success" or "fail". In addition, a form was filled out by the tester, detailing how the participant used the reader, and photographs were taken of the grip used to hold the reader. Subjective user responses regarding ease, comfort, and satisfaction were also recorded at the end of each part of the task.

Participants were told: "this is a test on a new system being developed that allows a user to navigate a PowerPoint presentation by swiping low visibility barcodes printed over a PowerPoint handout." This was purposely kept brief to make sure the participants only knew as much as they needed to know to perform the task. Instructions were given on how to understand and use the printout, but not on how to hold the reader, beyond which parts needed to be touched.

### 3.3 Task

Each participant was asked to use the reader to swipe the barcodes to navigate through the slides one by one in a prescribed order, stepping through every part of each slide. If the slide was not brought up after five attempts, the participant was asked to move on to the next slide. The participants went through the set of slides a second time doing the same thing.

The participants were given the following instructions on how to use the reader:

- Touch the finger contact band on the reader at all times.
- Touch the border of the paper at all times.
- The reader must be in flat contact with the barcode.
- Each swipe across a barcode must start and end on the wide band of lacquer.

In addition to this task, the participants were asked to complete the same task again using a mouse and keyboard. In order to present the slides in the prescribed order, the participants were asked to sort the slides before clicking through them. Both parts of the task were timed individually.

Half of the participants were asked to do one task first, followed by the other, while the other half of the participants did the two tasks in the reverse order. This was to allow for analysis into whether doing one part of the test first helped them be more successful in the other.

### 3.4 Aims

The aim of the user study was to determine the capability of the contact barcode reader with regard to areas of interest as follows:

- Intuition
- Effectiveness
- Efficiency
- Learnability
- Comfort & Health
- Satisfaction

The capability of each factor was measured by one or more sets of data and the reasons for the results were analysed through comparison with various aspects of the participants' behaviour. The aim was to see if there was correlation between the results and the behaviour of the participant, to uncover which aspects control the results and hence are the areas to concentrate on for further development.

## 4. RESULTS

The results were gathered from the questionnaires filled out by the tester throughout the tests. The tables show the numeric data from the tests combined. Each participant had two tries at each task. The results of each task are shown in separate bar charts. The findings are divided into the categories listed in the Aims section. All of the participants were familiar with the use of PowerPoint.

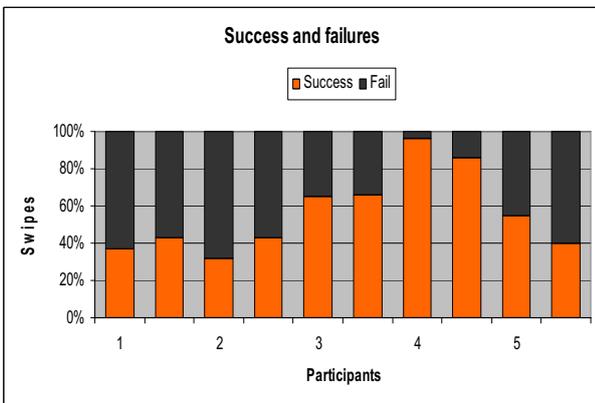


Figure 3. Percentage of successful results on 1<sup>st</sup> day.

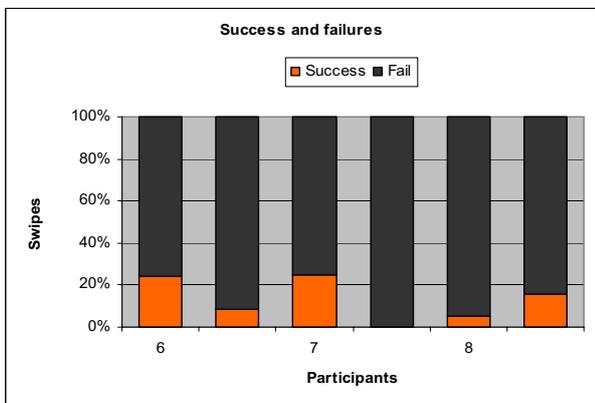


Figure 4. Percentage of successful results on 2<sup>nd</sup> day.

### 4.1 Intuition

The ease of the task when using the mouse or keyboard was on average rated as very easy. When the reader was used the task was rated on average as difficult.

The correct surface of the reader was used to contact the paper by all of the participants, and they all touched the finger contact band correctly. All participants held the reader in a pen grip, though each had an individual grip with variations in how much of their hand was wrapped around the reader. They all held the reader flat and did not have difficulty keeping the reader in contact with the paper.

### 4.2 Effectiveness

The average rate of success for the control was 95%, while for the reader it was 51% on the first day of testing and 13% on the second day. This highlights the potential of the reader to be very successful, but further studies are needed to pinpoint which factors determine success or failure.

The graphs above show fairly consistent results for the first part of the testing, which improved before dropping off for the last few participants tested on the second day. Any changes in performance between the first and second tries of each participant were minimal.

Possible reasons for reduction in success between the two days could include deterioration in the lacquer/paper interface, deterioration in the reader contact point, variations in individuals' ability, or conductivity variation in the paper brought about by humidity changes. Further work will investigate these factors.

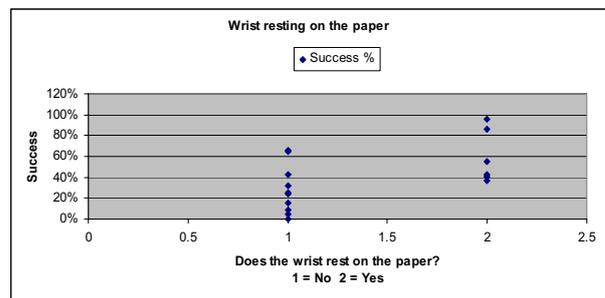


Figure 5. Wrist resting on the paper compared to success.

The previous graph shows that there is an apparent correlation between the participant's wrist resting on the paper and the success rate. There is greater success when the wrist rests on the paper, implying that the user has more control over the consistency of the swipes. Further testing would be needed to verify whether this is the case, or whether the correlation is due to natural variability.

### 4.3 Efficiency

The average time taken for the user to go through the slides in the control is 28 seconds, and 1 minute 12 seconds to complete the entire task including sorting the slides. The average time to complete the task using the PaperWorks pattern reader was 5 minutes 16 seconds. This was due to the time lag between swiping a barcode and seeing the result on-screen, and also the time spent on unsuccessful attempts. When the task was completed with a 96% success rate (Participant 4), this was done in 2 minutes 51 seconds.

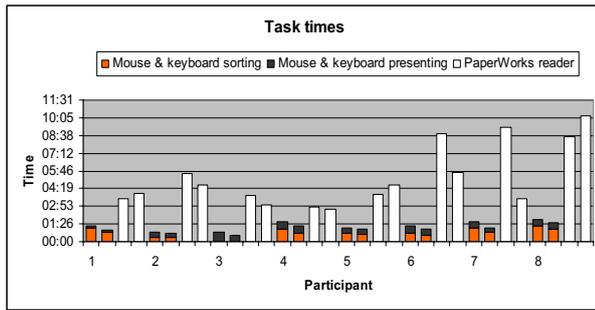


Figure 6. Task times for control and reader.

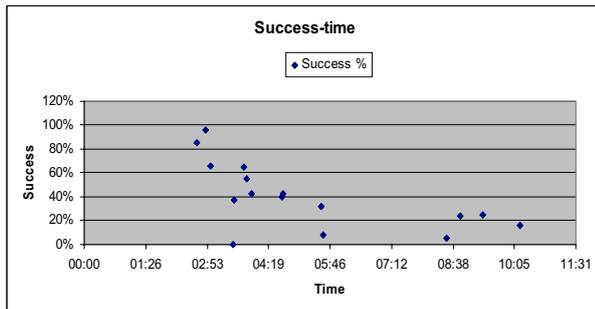


Figure 7. Time taken compared to success.

Figure 6 shows that the more successful the results were, the shorter the time the participant took to complete the task. This is due to time spent on unsuccessful swipes holding the participant back from completing the task.

#### 4.4 Learnability

There was a 5% decrease in success between the first and second attempts of each participant to complete the task. An increase in ability was seen in participants whose first attempts were in the middle of the range of success, about 30%-40% success; and also in Participant 8 whose initial results were very low, but managed to learn how to control the outcome for a time at the beginning of the second attempt. Other reasons could be that the participants did not understand the difference between what they were doing to create success and what they were doing when they had no success, thus making them unable to learn how to improve. Successful results were hard to maintain for several of the participants.

#### 4.5 Comfort and health

The average comfort rating for the control was comfortable, leaning slightly towards very comfortable, while for the prototype pattern reader it was rated as neither comfortable nor uncomfortable, leaning slightly towards comfortable.

All of the participants held the reader in a similar way to each other, using a pen grip. Minor differences between them are seen in different participants in each of the following areas, but there is little correlation between these differences and the comfort ratings. Participant 8 was most frequently the participant to hold the reader in a different way to the others, primarily due to being left-handed. The majority of the participants held the reader with their hand evenly spread over the reader, with fingers resting on the ridge of the reader; with a space between the thumb and index finger that was not filled by the reader, and with at least one finger wrapped around the front of the reader.

#### 4.6 Satisfaction

The average satisfaction rating for the control was satisfied, while for the prototype pattern reader it was unsatisfied. Comments included that it tended to be better when you were more forceful with it and paused at the end of a swipe, and that it was too unpredictable.

### 5. CONCLUSION

The prototype reader in the hands of certain users can give repeatable high levels of success. Overall however, the performance of the reader was poor when compared with the control. Possible reasons are believed to be wear of the printed patterns, which had to be re-used between trials, and changes in ambient humidity which have been shown to affect the conductivity of the printed patterns.

Further work is required to investigate the factors contributing to the variability in performance of the overall system.

### 6. ACKNOWLEDGMENTS

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# The Supporting Role of Paper in Multi-tasking

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## ABSTRACT

Despite the proliferation of task planners, though useful for supporting metawork activities, they are not adequate for supporting the detailed minute-by-minute management of interrupted tasks. I present empirical data that shows the extent to which information workers multi-task and are interrupted throughout the day. Yet in spite of such frequent switching of tasks and projects, people are fairly competent at resuming work. I argue that paper plays an important supporting role in people's ability to accomplish work with high levels of multi-tasking. I discuss ways that technology might draw on some of the affordances of paper to support multi-tasking.

## Keywords

Multi-tasking, task planners, interruptions.

## 1. INTRODUCTION

The topic of attention overload and multi-tasking has received quite a bit of attention in the media and in popular books. In recent years, multi-tasking and interruptions in the workplace has also begun to receive serious empirical attention in HCI. For example, empirical studies have focused on identifying the extent of multi-tasking and interruptions and how they affect tasks [8], the recovery of tasks after an interruption [5, 11], and timing of interruptions, e.g. [1]. Anecdotal and empirical evidence suggest that constant interruptions are a way of life for information workers.

The widespread attention to multi-tasking has not escaped the eyes of those involved in commercial ventures. In recent years as well there has been a proliferation of various types of digital task planners. A recent Internet search revealed keywords such as "Time boxing", "count down timers", and "alarm masters" as features marketed in digital devices to help people manage their tasks and their time.

In this paper I will describe an overview of some empirical results showing the extent to which information workers multi-task and are interrupted in the course of their daily work. I will argue that people have a remarkable ability to accomplish work despite experiencing constant interruptions throughout the workday. This ability is due to people's cognitive ability to keep track of multiple events in memory but also it is due to people's use of paper to externalize and record salient and important aspects of work that is interrupted.

## 2. RESEARCH SETTING AND METHODOLOGY

The empirical results reported in this paper are from fieldwork conducted at two different companies in the southwestern U.S. over a thirteen-month period. The first company, with 24 informants, provides information technology, accounting and financial services. Two teams were studied, one in charge of maintaining the financial systems, and one in charge of

maintaining different transactions and accounting systems. The second company, with 12 informants, specializes in providing process reengineering solutions and software systems for small and medium-sized medical practices.

Ethnographic "shadowing" observation was conducted similar to those done in previous time management studies [12], [15]. The researcher sat behind the informant in her cubicle or office where it was possible to observe all her activities. All of the individual's actions were timed to the second, e.g. opening a computer application, making a phone call, or typing in a Word document. Interactions with others were also observed and timed. Clarifications were asked at the end of the day. Mintzberg's structured observation method [11] was used to design an activity tracking log to record time stamps, data about the type of event (e.g. "responding email to AMX"), the artifacts using during the action (e.g. phone, Excel, sticky note, calendar), and the people interacting. Each individual was shadowed for three and a half days. The informants had varied job roles and represented a range of information workers: software developers, financial analysts, support engineers, project leaders, and managers. Further details of the methodology are reported in [3], [9].

### 2.1 Results: the extent of fragmented work

I will briefly give an overview of the main results that are relevant to discussing the role of paper in supporting multi-tasking. More details on the specifics of interrupted work of this study can be found in [3], [9]. The results showed that the informants' typical workdays are characterized by a high level of multi-tasking. First, the informants averaged work in 12.2 (sd=5.3) different projects<sup>1</sup> per day. If we consider events such as telephone calls, interactions with another, or writing on a Word document, then people switched events an average of every three minutes (mean=3 min. 5 sec, sd=2 min. 51 sec.). When considering work at the level of projects (or 'working sphere', see [3]) then people switch their working spheres every 10 min. 29 sec. (sd=2 min. 51 sec.) on average. People were fairly good at resuming interrupted work, resuming 81.9% of their interrupted tasks on the same day. However, the bad news is that people worked in an average of 1.92 (sd=1.79) different working spheres before resuming the interrupted task. In other words, interruptions are nested: one gets interrupted, and then is interrupted again by yet another task. Fortunately this is not *ad infinitum*.

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<sup>1</sup> Projects at the workplace in this study are not limited to what is organizationally defined (e.g. by one's manager) or even to what is directly related to one's job description. For example, a project can be work on a software application, it can involve planning a departmental budget, but it can also involve planning a company picnic or serving on a task force.

## 2.2 Accomplishing work when multi-tasking

Thus, so far, I have presented data that shows that multi-tasking is a way of life for many information workers, and the extent to which they switch events and projects throughout the workday is very high. Yet despite this high amount of fragmentation in their work, what is perhaps most remarkable is that people are able to accomplish their work at all.

Most people prefer to work in a monochronic workstyle, where they work on one task to completion before turning to work on another task [5]. For the informants described here, a polychronic workstyle, where they are constantly handling multiple tasks and switching among them, is the norm, or expected behavior.

How do people cope with dealing with a workstyle that is not their preference? People cope by trying to keep track of the current state of their various working spheres. When people are interrupted they need some mechanism to remind them of what they were working on at the point of interruption. These mechanisms that the informants used happened to mostly be paper notes.

The post-it note is commonly used as a reminder of work that had been interrupted and needs to be resumed. For example, one informant had seven notes describing actions to be taken in different working spheres [3]. One exception to the use of a paper artifact was the use of the email inbox folder to keep track of work. Not only do the subject headers of emails serve as visible reminders of pending work but often informants send messages to themselves with the 'cc' function as a way of reminding themselves of what needs to be done.

As Malone discovered by observing office desktops [8], the placement of documents in strategic locations on one's desktop can help one organize work. The informants used such a strategy of maintaining stacks of paper on their desks with printouts of email messages or meeting notices. Informants sometimes annotated the messages. The position of piles of paper can indicate priorities, e.g. if closer to the center of the workspace then the pending work is more urgent. Post-it notes are often placed on the rim of the computer monitor where they can most of the time be in one's field of view and remain there while the work is still pending. Often they are annotated and updated to indicate the status of the working sphere.

## 2.3 Paper as a medium for keeping track

Paper use is a simple strategy that enables people to perform polychronic work (though most prefer a monochronic workstyle). Strauss was long aware of the prevalence of polychronic work and described that work can be viewed as trajectories of multiple tasks [16]. The typical information worker manages an average of twelve different working spheres; multi-tasking might be viewed as a progression of work while switching along the trajectories of many different working spheres. Consequently, one needs to mark the points in the different trajectories where work has temporarily stopped due to interruptions, in order to resume the task later.

But why use paper as a marker along such a trajectory? As discussed at the beginning, there are a myriad of digital devices that are designed to support task and information management. I offer the following observations on why paper best serves the use as a reminder in supporting the minute-by-minute switching among these different work trajectories. These observations of multi-tasking confirm and extend the affordances of paper described by Sellen and Harper [14] in supporting collaborative work.

*Rapidity of use-* Interruptions can occur in bursts. At other times there can be long periods of solitary work performed without interruptions. During these "burst times", paper seems to be the ideal medium for noting critical aspects of the interrupted task. There is little "startup time" in using paper to note down an event occurring in real time, as opposed to using digital devices to record reminders. Sometimes informants would just note down an abbreviation as a marker to indicate that the task must be resumed. Notations about interrupted work are done in real time, analogous to taking down phone messages as the caller speaks. Especially during these "bursts" of interruptions, paper affords the ability to note down critical information rapidly, in a way that can keep pace with the switching.

*Field of view.* It is not only the placement of documents on the desktop that can serve to organize work but also the placement of paper artifacts in various locations of the office environment: on the computer monitor, the cubicle wall, the back of the chair, etc. The position of paper can be easily manipulated to be placed in the user's field of view (e.g. on the back of the chair when one enters the office) or on the periphery of their visual attention depending on the urgency of the reminder. Post-it notes placed on the rim of the computer monitor enable them to be on the near periphery of vision as one uses their computer. Paper on the desktop can be easily arranged to be in or out of the field of view depending on whether resuming the interrupted task is high priority, whether there is a deadline, or whether it can be placed on the 'back burner'. Reminders on desktop or laptop task managers, PDAs, or tablet computers are not always in the field of view due to limited screen real estate, if the application is not open, or if the device is simply not turned on.

*Flexibility of use-* Multi-tasking involves very dynamic work. Interruptions also tend to be nested [9]. People are interrupted, and then typically interrupted again from that interruption. When people switch working spheres often the environment changes. New windows might be opened on the computer or papers rearranged on the desk. People might even leave their office. Paper is a flexible medium for recording the state of such dynamic work; notes can be taken as people switch environments, they can be passed to others, and they can be physically rearranged to associate information. When a task is resumed, then the reminder can be tossed away, or the note can be quickly updated.

*Externalization of task information-* In addition to an important role of paper as supporting collaboration through its 'at-a-glance' properties that provide a shared reference [14], paper can also be used to externalize very personal representations of work. The informants described in this study often used acronyms or personal abbreviations to note information about interrupted tasks. Individuals also have unique styles for positioning paper reminders. While certainly computer media could be used for personal representations, paper affords more versatility in personalizing a representation concerning a task. Sketches, one's handwriting, the writing instrument used, and the placement of notes can provide contextual cues that are tailored to an individual. These cues can serve to aid episodic memory recall. Such memory prostheses operate, as Tulving [17] describes, by enabling people to recall experiences associated with the initial episode. Paper's versatility affords people far more options to personalize their representation of the reminder compared to digital media, especially valuable as an aid in recalling an event.

*Accessibility while mobile-* More than ever, workers are becoming extremely mobile, where they travel much of their

work time. For these nomadic workers, work is done wherever the person happens to be: in the airport, a café, a hotel room, a customer site, or elsewhere. Nomadic workers experience interruptions and task-switching as information workers but they also experience disruptions in their work due to the contingencies associated with travel. This can affect access to electronic artifacts. For example, when people are in transit it is not always convenient or even allowable (as part of air travel) to use laptops or PDAs to enter information. Paper then can be a useful placeholder for reminders, free of the overhead of booting up a device, using battery life, charging devices, or wireless connectivity. Further, its portability is an asset as nomadic workers must carry their “mobile offices” with them as they travel site to site.

While task planners can be useful for organizing metawork<sup>2</sup> I have argued that so far, digital task planners are not well-designed to effectively support the minute-by-minute notation of items related to interrupted work. The design of such systems has not taken into account the situated nature of work, especially the high degree of multi-tasking that is becoming more recognized. An interruption generally occurs spontaneously. Yet clicking on a task planner application on the desktop or PDA, or even moving a window on the desktop to access the application, or for that matter, even opening an application, takes time. Even the short time spent in preparing the digital planner for use can result in the loss of critical information (and human memory) about the interrupted task.

As mentioned, digital task planners take up valuable screen real estate on the desktop or laptop computer. The utility of paper is that it can easily be moved when it begins to use up valuable desk real estate but the information can still be visible and easily retrievable. Though PDAs can display information as a peripheral device to the laptop or desktop, chances are that the reminder note is not likely to be in one’s field of view but must be retrieved.

The task planner can itself be the source of interruptions. Alarms, blinking signals, and other stimuli can become external sources of interruptions. Some informants in this study were interrupted by digital signals, such as blinking icons to signal incoming emails. Paper can also be distracting (e.g. when in the field of view) but one can become habituated to the paper source as opposed to receiving an abrupt new change of stimulus such as a blinking icon. Tulving [17] attributes episodic memory recall to both a memory trace and a cue (e.g. the paper note). Thus, a paper note sits in the background of one’s environment and only moves to the foreground when the information becomes relevant (i.e. when the memory of the interrupted task is triggered by the paper note). Contrast this with the use of task planners, where one must first remember some aspect of the event (or to remember to check the planner) and *then* access information about the event.

### 3. Designing for multi-tasking support

Observations of how people use paper to support their multi-tasking activities lead to design implications. While so far paper seems to be the best medium for swift and flexible note-taking, there are some ways that technology could be designed to improve the practice of tracking and planning for multi-tasking work. A number of digital paper technologies are emerging and this area can hold promise for supporting multi-tasking. This

technology is an interesting area to explore because it has a potential for offering similar affordances to paper—it can be easily moved in and out of the field of view, is very portable, can be personalized (e.g. one can use handwriting), and it can be updated easily. Though PDAs offer some of these affordances, one key difference is that it is impractical for numerous notes on PDAs to be continually displayed in one’s field of view. Some particular design considerations for how technology could support multi-tasking are as follows.

*Spontaneous use-* Interruptions are unpredictable and in fact, people are almost as likely to self-interrupt as to be interrupted by external sources [9]. In addition, task-switching and interruptions can occur at a fast rate. Reminder mechanisms therefore need to capture information about the interrupted task—before one moves on to the next interruption. A digital device for keeping track of interrupted work therefore needs to be able to be accessed and used spontaneously. Opening an application or turning on a (PDA) device is too cumbersome for capturing events that change very rapidly. If the device is digital paper (using a digital pen), it must be at-hand, enabling immediate strokes.

*Mobile accessibility-* People are working more ubiquitously—in the office, on the train, from the home, at different company sites—and are concerned with resuming interrupted tasks even when they are not in their office. Reminders placed in strategic locations in the office are useful, yet it would be also valuable to be able to access reminder information when out of the office. One interesting direction is a hybrid approach like PADD [4] that enables one to interact with a document in either digital or paper form. As paper, such a hybrid note can be posted in the office and moved around. As a digital document in the computer, it is not tied to location; it can be accessed from anywhere.

*Increasing contextual cues-* Multi-modal devices could be explored as ways to make it easier to resume interrupted work. For example, post-it notes that also contain audio information would provide additional contextual cues for retrieving information about an interrupted task. Rasa [10] is a multi-modal tool that employs both speech and the design of post-it notes but these are bound to a wall display and a limited set of symbols.

*Directly linking to information-* A way that digital paper can offer an additional affordance to paper is by enabling direct linking from the note to task information stored on the computer. Such direct linking can ease the resumption of an interrupted task; one need not search for task information but can access it rapidly. For example, if one is interrupted in the middle of working on a Word document, a note could enable a direct link to that part of the document where one was interrupted. This saves time in reorienting back to the interrupted task.

*Visualizing work-* A different approach than digital paper is providing an electronic visualization of one’s current state of their ‘line of work’, as Strauss [16] describes, which would be invaluable in aiding people in assessing how far along they are in their different work trajectories. Such a visualization could show what tasks have been worked on, when they have been interrupted, and which tasks have been neglected for some time. In order to not impose extra work on the user for inputting task information, exploration needs to be done on how task information could be extracted from other sources, for example, perhaps even from reminder notes.

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<sup>2</sup> Metawork refers to the work that is concerned with the overall management of activities such as checking the overall progress. It can also refer to organizing email, organizing one’s desk, etc.

## 4. Discussion and Conclusions

In their study of a small office, Rouncefield et al. [13] noted how paper serves as a spatial and temporal marker of activities. Similarly, Sellen and Harper [14] showed the importance of paper in supporting collaboration in a large organization. This current study extends these findings. Whereas these researchers focused on how *paperwork* in its role at the workplace (i.e. the writing, filing, organizing and retrieving of paper documents) can help coordination and collaboration, in this paper I discuss paper in its *supporting* role for the coordination of a person's multiple work trajectories. Nearly all of the work conducted at the current field sites was done electronically, using computers, PDAs, landlines, and cell phones. However, ironically, digital devices were not used to coordinate the electronic work. Digital task planners are useful for supporting metawork or long-range planning. They are less useful for helping people keep track of the minute-by-minute changes as people switch among working spheres.

In their study of mobility, Luff and Heath [7] point to how the easy transport, manipulation and availability of paper medical records supports collaboration [7]. In addition, I describe here how paper supports individual task management when people are mobile. Paper is robust against failure in different environments. Unlike cell phones or the Internet which rely on connectivity, paper is always usable irrespective of the environment.

I have deliberately remained impartial as to whether interruptions are a good or a bad thing. In Rouncefield et al.'s study, the office workers enjoyed interruptions as sociable encounters. In other cases they are viewed as disruptions detrimental to work [6],[1]. A third view is more nuanced: when interruptions concern the context at-hand then they are beneficial; otherwise when an interruption forces one to switch contexts to respond to the interruption then they are detrimental [9]. But in any of these cases, they lead to a break in activity. The burden of interruptions is usually on the person interrupted, to reorient back to the original activity. It is here where paper makes a difference.

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# The role of paper in the future of printed electronics

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## ABSTRACT

Paper is the raw material for much of the output of home and commercial printing. Printing methods that were developed for and matured in commercial printing are now being applied for electronic device fabrication in applications areas such as printed electronics, printed displays and photovoltaic devices.

Over the years digital methods have made significant inroads into printing and one significant technology in this is inkjet.

This paper examines the potential use of paper substrates in printed electronics and the technical issues involved. The paper uses inkjet printing to illustrate these technical issues. However, much of what is discussed also applies to other printing methods.

## 1. INTRODUCTION

The use of paper as the substrate in printing processes can be considered to be a mature technology. However, there are now new applications being developed that, while using the existing technologies require substantial modifications to make them a realistic option in the market place. One of these is printed electronics, the ability to print electronic components and complete devices onto substrates.

These devices are now beginning to appear and the market research listed in this paper suggests that we are now on the cusp of widespread application.

Paper would appear to have a place in this new technology but in order to understand this and optimise products for these applications the printing characteristics must be re-examined, particularly considering fluid – paper interactions.

One of the key strengths of paper as a substrate for printed electronics is its widespread acceptance for many existing applications. The future may well lie in mixed documents, containing both conventional print and printed electronics. One technology that looks ideally suited to this is inkjet printing and this printing method is used by way of illustration in this paper.

This paper first of all outlines the reasons why printing is being considered as an electronics fabrication method and some of the substrates and techniques being tested. It then looks at the components of a printing system using inkjet as an example in order to identify the areas needing technological development. Finally, it examines fluid – substrate interactions, the key issue facing the use of paper in this market.

## 2. Why print electronics?

Printed electronics for our purposes includes the creation of electronic or opto-electronic circuitry using some kind of printing

method. There are a number of applications benefits to printing electronics.

1. It is a ready route to flexible components. Examples of these include flexible displays for mobile devices and “electronic papers”. Here printing competes with vapour deposition and will probably be cost competitive for many devices. This is because vapour deposition has the expense of large vacuum chambers and printing could be capable of the assembly of devices using multiple technologies (batteries, aerials, memory, interconnects etc).
2. It allows electronics to be readily integrated as a part of other printed media by printing them on the same press. This gives access to products such as novelty cards, Radio Frequency Identification (RFID) and smart packaging. There is already significant interest in this from the packaging sector as there are many potential applications here. It is interesting to note that in all these cases the printed item would combine both conventional printing and printed electronics.
3. Printing is much faster than traditional wafer fabrication. One estimate puts this speed difference as 4 orders of magnitude per device. This speed difference is the key to low cost production and is the facilitator of disposable electronics such as electronic tickets, rudimentary examples of which already exist using conventional printing.<sup>1</sup>
4. Printing has a lower capital investment cost than other fabrication means. It is estimated that a printed electronics plant will cost \$30 million, just a fraction of a \$3 billion conventional silicon fabrication plant.<sup>2</sup>

In addition to the applications side there is an interesting business case for printed electronics as opposed to conventional silicon based fabrication. This is the possibility of new production economics compared to silicon based systems. These are subject to fabrication plant cost inflation driven by the market expectation that Moore’s Law (the regular doubling of computer processing power) will continue. Inkjet in particular could change this – see Section 4. It has a different production cost base capable of highly customised runs and small batch sizes facilitating disposable electronics.

Sales of printable electronics products are forecast to reach \$1.6 billion within a couple of years and could reach over \$30 billion by 2013.<sup>3</sup> Smart packaging alone is forecast to account for over \$1.1 billion in printable electronics components by 2011 (mainly RFID tags) growing to \$4.2 billion in 2013.<sup>4</sup>

The potential benefits are large but some major challenges still exist.

1. For RFID to enter the mass market it is estimated that costs need to come down to \$0.10 or \$0.05 but it the consensus that this may take 8 years.<sup>5</sup> There is little chance that silicon will hit this price point – the price of the cheapest silicon chips (without all the rest of the RFID assembly) has stuck at \$0.05 for decades.<sup>6</sup> Printed RFID could potentially hit these price points for mass produced items using conventional printing technologies.
2. Print quality. The metrics of print quality change when moving from conventional print to printed electronics. In conventional printing these are usually based around macroscopic measures (colour gamut, tonal rendition, visual sharpness etc). However, printed electronics will bring in a whole new set such as printed dot morphology, line continuity and metrics for microscopic defects and layer registration.

### 3. Printing substrates and techniques

So far, commercial activity for printed electronics has largely been confined to glass and a narrow range of plastic substrates. Glass will continue to be an important substrate for printed electronics in rigid displays due to its excellent optical and mechanical properties.<sup>7</sup> Substrates for printed electronics are and will probably continue to be dominated by plastics, in particular PEN because of its greater dimensional and thermal stability.<sup>8</sup> For smart packaging and other applications paper is seen as potentially useful. Printing on paper is very logical and it would seem to be essential to the emergence of a significant smart packaging sector. By 2013, it is forecast that paper substrates for printable electronics will reach \$0.5 billion in annual sales.<sup>9</sup> This looks likely to consist of specialist coated papers, for the technical reasons outlined in Section 5.

Virtually every traditional printing mode (screen printing, flexographic, gravure) has been or is currently being used for creating circuitry of some kind.<sup>1</sup> In the future all of these are likely to co-exist in the printed electronics market and the choice will be determined by the normal parameters such as run length, feature size and variable data requirements. Conventional printing systems such as flexographic, offset and gravure are best suited to mass production and this will likely continue in printed electronics. Screen printing also has a place and some early commercial electronics printing activity such as the creation of RFID and novelties is being done in this way.

However, as in conventional printing there is a lot of interest in digital printing, which can usefully be defined as using a digital file or document as the input to a printing mechanism.<sup>10</sup>

Although it looks as if both inkjet and toner based systems will translate into printed electronics it is inkjet that is currently attracting the most attention. The technical attributes of inkjet make it best suited to mass customisation, small batch size and simple circuitry. Inkjet appears set to become an enabling technology for on demand production in printed electronics, imparting design flexibility and rapid design testing. As a result this paper uses inkjet technology to illustrate some of the issues

as printing makes the transition to the fabrication of electronic devices.

### 4. The inkjet printing system

In order to understand the issues involved with the move to printed electronics it is necessary to look at the printing system as a whole.

Figure 1 illustrates a key aspect of the inkjet system that has important ramifications for understanding the issues involved in the development of this market.

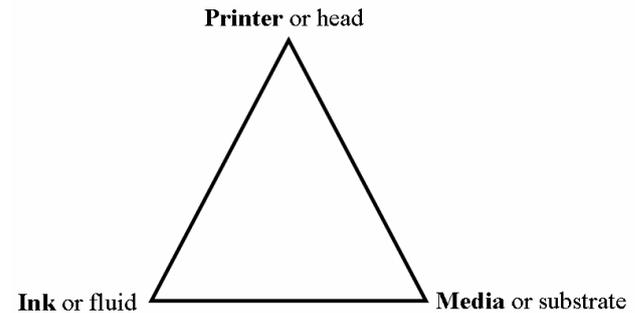


Figure 1 The inkjet system

An inkjet system can be considered to consist of 3 overall elements, a model that can be used for other printing methods too. In order for the system to work each must be compatible with the other two. For example, the ink must wet the media but not run off before drying. Similarly the surface and physical characteristics of the media must allow it to reproducibly transport in the printer. Finally, the ink must be compatible with the whole delivery system in the printer, from cartridge to nozzle. The three elements are illustrated in **bold** in a traditional printing application but Figure 1 also contains reference to the extension to Printed Electronics use. In this case the system can again be considered to consist of 3 overall elements and as in traditional printing each must be compatible with the other two. However, this appears to be given lower emphasis within the Printed Electronics community as the issues do not yet seem to have been dealt with as a complete system.

For example, from the perspective of the head manufacturer the issues are around compatibility of the printing fluid and the inkjet head.<sup>11</sup> Similar perspectives are taken by fluid manufacturers. This could turn out to be an impediment to adoption of paper into this area. Although there is some basic work on ink / media interactions published<sup>12</sup> the area does not seem to have the attention that this area warrants.<sup>13</sup>

### 5. Fluid – substrate interactions

The various aspects of ink and media interactions must be revisited for printed electronics, particularly when considering paper as the substrate. However, previous knowledge from conventional printing is still applicable here.<sup>14</sup>

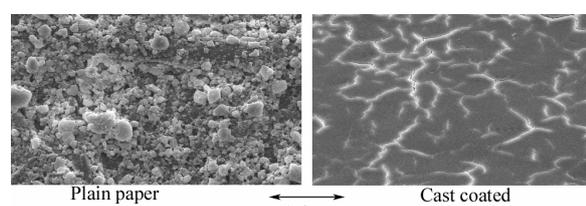
When a drop of inkjet ink is printed on media it has been shown that there are 3 phases in the process of forming the final printed dot.<sup>15</sup>

1. Inertial spreading. The ink droplet which may be of perhaps 5 to 100 picolitres hits the media at around 10 m/s. The

droplet spreads due to its own inertia to an extent that is mainly governed by the kinetic energy, viscosity and the surface tension of the drop. This latter property is one that can be easily manipulated to modify the final dot diameter.<sup>16</sup>

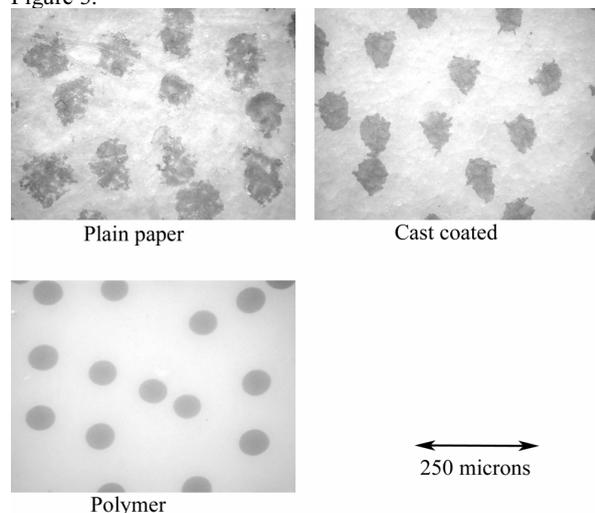
- Absorption. The droplet some to rest at a quasi-equilibrium position governed by the wetting characteristics of the media by the ink. On a smooth, isotropic medium this would be expected to result in a drop of near circular horizontal profile. However, when dots are printed with any level of overlap ink spreading from one drop into another takes place.<sup>17</sup>

Many papers used in printing are not isotropic. For example, plain paper and cast coated papers have significant surface features that influence the form of the printed drop. These are illustrated in Figure 2.



**Figure 2 SEM pictures of paper surfaces**

Inkjet images made on these types of media are not in general constructed of uniform round dots, as illustrated in Figure 3.



**Figure 3 Inkjet ink spots by light microscopy**

The fibrous nature and uneven surface of the plain paper leads to a rather diffuse spot. The micro cracking of the surface of the cast coated product leads to some ink flowing like rivers in valleys, again producing spots that resemble fibrous products. Clearly these products would not produce acceptable results for printed electronics.

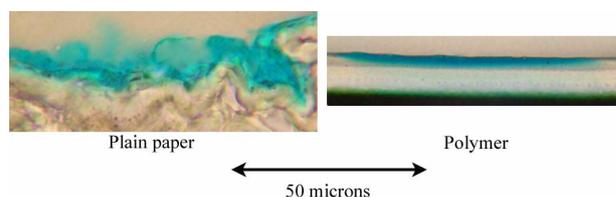
By contrast a polymer coated product produces well delineated isotropic dots on this scale and thus illustrates recording characteristics much more suited to printed electronics applications.

- Evaporation. The final stage of the process is the evaporation of the ink liquids. It is generally the case for plain paper and

conventional inkjet media this take place at a much slower rate than absorption. As it is the balance between absorption and evaporation that drives the final dot shape it is usually the absorption step that is the main driver for dot morphology. It has been shown that this results in an optical density profile for the printed dot that is roughly parabolic in shape.<sup>15,17</sup> This can be envisaged as the dome shaped drop on the surface being sucked down into the media as illustrated photographically in the literature.<sup>15</sup> However, given that in some cases special circumstances do occur it is worthwhile considering some of these.

When printing onto a non absorbing medium such as glass or metal the process is dominated by evaporation. In this case the density profile is not parabolic but due to capillary processes dries into a toroid or donut shape sometimes known as a “coffee-ring” effect.<sup>18</sup> Also, the formation of a “cake” of particles at the media – droplet interface can in some cases result in the absorption of liquid being retarded, even on supposedly porous media.<sup>15</sup>

In addition to the microscopic evaluation of dried dots as illustrated by Figure 3 a further practical method of evaluating media for their dynamic behaviour to fluids is by dynamic contact angle measurement.<sup>19</sup> However, there is a further attribute that is important for paper in the transition to printed electronics. This is the fact that the media also have a depth perspective to the image recording. This is revealed by examining thin sections through the media by light microscopy, as illustrated by Figure 4 from a previous publication<sup>20</sup>.



**Figure 4 Cyan ink spot cross sections**

Figure 4 shows that in the case of the plain paper the colorant layer is thick and amorphous whereas in the case of the polymer media it is confined to a thin uniform layer near the surface. In addition Figure 3 shows that the spots on the polymer media have a lower surface area. This is a model much more likely to succeed in the case of printed electronics.

## 6. The challenges remaining

Printed electronics looks set to happen. At the time of writing the majority of printing is still done by conventional printing methods. These methods will continue to be important in the longer term, particularly for high volume, low cost mechanisms that will be necessary for disposable electronics. However, to make this happen costs will have to be reduced. Lower cost functional inks and substrates will need to be produced with the correct price / performance ratios.

There are further challenges for the newer digital technologies. The fluid / substrate interactions covered in Section 5 are one major issue. The registration of successive layers is another problem to be faced, particularly as substrates such as paper tend to swell, cockle and shrink during the printing and drying

process. Some form of optical feedback will probably be necessary here and initial work on this is now taking place.<sup>21</sup>

Finally, there is the issue of de-inking for paper recycling. As we move towards paper printing for disposable electronics for applications such as packaging the potential environmental and recycling issues need to be addressed. These are already a cause for concern in conventional digital printing and printed electronics is likely to add another dimension to this.<sup>22</sup>

It is unlikely that one printing system will prove appropriate to all these needs. As with conventional printing the solution probably lies with hybrid systems, combining the best attributes of the various deposition methods.

## 7. Conclusions

Controlling the morphology of the printed dots or elements is key to making paper substrates work for printed electronics. Amorphous or irregular structures such as those exhibited by plain and cast coated papers in Figure 3 are unlikely to be of use in anything other than the most coarsely printed electronic component. However, dot shapes such as that exhibited by the polymer coated product in Figure 3 are likely to be much more acceptable.

This polymer coated material is an example of the sort of complex multilayer coated products that have evolved for the highest print quality in photo printing. It is this knowledge and technology that looks set to become important in the new applications.

It is normal to see demonstration prints of printed electronics on photographic grade inkjet papers. These give excellent image quality but because of the resin coated base do not withstand the sintering temperatures of silver laden ink. However, they do point to the sort of technologies that will be needed in the future of paper in printed electronics.

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