Only Touching the Surface: Creating Affinities Between Digital Content and Paper

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ABSTRACT
Despite the wide-ranging recognition that paper remains a pervasive resource for human conduct and collaboration, there has been uncertain progress in developing technologies to bridge the paper-digital divide. In this essay we discuss the design of a technology that interweaves developments in new materials, electronics and software, and seeks to provide a cheap and accessible solution to creating new affinities between digital content, in whatever form, and ordinary paper. The technology and its design draws from a broad range of field studies, including research in classrooms and museums. These delineate the requirements and considerations that inform solutions to enhancing paper whilst preserving its integrity. The paper also discusses a naturalistic experiment, an evaluation in a museum, where we assessed the technology and the solution. We also chart the progressive development of this solution and the ways in which seemingly simple actions and issues became reconstituted as highly complex technical and analytic problems.

Categories and Subject Descriptors
H.1.2 [**Information Systems**]: User Machine Systems

General Terms
Design, Human Factors

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ubiquitous computing, tangible artefacts, paper

1. INTRODUCTION
Some of the most interesting developments within CSCW in recent years have emerged from the growing commitment to ubiquitous computing and exploring the ways everyday objects and artefacts can be augmented with computational resources. Research programmes in Europe, North America and Japan have directed substantial funding towards these initiatives, and leading industrial and academic research laboratories have developed a diverse range of ubiquitous 'solutions'. These developments mark an important shift in CSCW, a shift from conventional collaborative systems, to a concern with the interrelationship between objects, artefacts and technologies; a shift that is having a corresponding impact on social science research. Surprisingly perhaps, given the growing commitment to the ubiquitous and the tangible, there is a mundane, even humble artefact that pervades our ordinary lives - at work, in the home and almost everywhere else - that has received less attention than one might imagine. Indeed, despite a substantial body of social science research delineating the significance of the artefact, and technical developments that have attempted to refashion, reshape, even replace the material, paper remains a fundamental resource for many human activities and forms of collaboration.

In this paper, we would like to revisit the long-standing interest in CSCW with paper, and in particular, to discuss a seemingly simple 'solution' that will enable people to create affinities between material documents and digital resources. The solution does not rest upon replacing paper with a paper-like substance, nor with transforming the character of paper, but rather with enabling paper to support systematic links with digital content whatever that might be. The solution is not primarily concerned with writing, as with other developments, but rather with reading, and enabling people to access, or create, connections between any point on any page, of a document, book or whatever, and digital resources. This simple solution could be exemplified by considering the enhancement of an educational book associated with a television series. Such a book could be augmented to enable the reader to point to pictures or text on the page and gain associated information - video clips and the like - on a workstation, a PDA or television set. The solution would provide a vehicle for interlinking paper with a range of computational devices and resources and would suggest how a mundane but important artefact could be interwoven with a range of tools, technologies and objects within an environment. In other words it would suggest how conventional paper could feature in initiatives such as ubiquitous and pervasive computing.

In this paper, we discuss one solution and its development over the past three years as part of Paper++, a pan European project funded under the Disappearing Computer Programme. We discuss the emergence of the solution and the ways in which it resonates with observations and findings from empirical research, both our own and studies by others [20, 12, 13, 34, 9, 29]. We chart how it rests upon developments in inks, printing, electronics and software, developments that appeared to provide a simple and cheap solution to a pervasive human problem. We discuss the ways in which the solution emerged and how the unanticipated complexities of seemingly mundane materials and artefacts, posed critical problems. Finally, we discuss a 'naturalistic experiment' in which school children used the solution during their visit to a museum and were able to gain access to a range of resources; resources that enabled interaction and collaboration. In the course of this project, certain difficulties emerged that required reconsideration of the approach - both in terms of the technology and how it could be exploited. These raised questions regarding our understandings not only of an everyday object and how it figures in collaboration and interaction, but also for how we consider the development of augmented everyday objects.

2. BACKGROUND

One of the more impressive developments within CSCW has been the emergence of a substantial body of naturalistic research concerned with conduct, communication and collaboration in everyday settings. These studies have provided empirical findings and conceptual distinctions that have allowed us to reconsider, even respecify many of the more traditional ideas concerning the ways in which tools and technologies, objects and artefacts feature in action and interaction [e.g. 28, 3]. Many of the earlier studies focused on complex organisational environments, environments that were subject to the deployment of a range of sophisticated tools and technologies. Ironically perhaps, these studies discovered over and over again one remarkable fact - despite the pervasiveness of new technologies, accompanied in many cases by management's attempt to reshape traditional practice and procedure, paper remained and remains a critical feature of work and collaboration. Many of the examples are well known - flight strips in air traffic control [9]; the paper timetable in London Underground [11]; the traditional medical record in primary health care [12]; the tickets in financial dealing rooms [13]; the documents reviewed by lawyers [34]; and so on. The significance and purpose of paper within these domains and many others has been splendidly drawn together in Sellen and Harper's book - The Myth of the Paperless Office [29].

In passing it is worth mentioning that more recent empirical studies in CSCW with an interest in going beyond the workplace have once again discovered the importance of paper for ordinary conduct and collaboration. Studies of the domestic environment, classrooms, museums and galleries and the like, have found that paper remains a pervasive resource, a resource that is often used within and alongside digital technologies. In general these studies have identified a range of characteristics of paper and paper use that seem critical to human conduct, communication and collaboration, characteristics that are sometimes referred to as affordances. Once again some of these are well known but it is perhaps helpful to mention one or two. Paper is mobile, portable between different spaces and regions; it can not only be relocated and juxtaposed with other objects and artefacts, but is micro-mobile, it can be positioned in delicate ways to support mutual access and collaboration [20]. Paper is annotated in ad hoc and contingent ways; people can recognise those annotations, track their development and often recognise who has done what. Paper retains a persistent form and preserves the layout and character of art work that is produced on its surface; it can be pictured, memorised, and navigated, even scanned, with ease. These characteristics and many more not only support complex individual activities but ironically perhaps, provide a firm foundation to many forms of collaboration, be it synchronous or asynchronous, co-located or distributed.

One additional issue is worth raising; an issue that is surprisingly under-explored within workplace studies. Paper has provided a critical resource to enable people to use even conventional information systems. Paper is used with, and alongside, digital technologies and people spend much time and effort creating, sustaining and transforming the relationship between paper documents and digital resources. Students, teachers, journalists and the like edit text on paper and transpose those corrections to digital copy, architects modify paper plans and integrate those changes in the CAD system, administrators litter their workstations with reminders, diary notes and the like, and booking clerks labouriously write down the details of your travel arrangements before trying to enter the information into a system. Paper is not just an independent resource that somehow has continued to survive despite attempts to remove it, but rather is an integral feature of using new technologies. It is somewhat surprising that such relatively little effort has been devoted to enhance the relationship between paper and the digital.

3. DISCRIMATING APPROACHES

Given observations concerning the pervasive nature of paper, it is perhaps not surprising that the capabilities of paper documents might suggest to researchers in ubiquitous computing implications for developing new technologies. This may be by replicating some of the paper document's capabilities, for example by making applications more portable or mobile. Or it may require more radical technologies, for example by reconsidering the display and input technologies so that they might enhance such activities as reading, writing and in other ways interweaving the paper and digital worlds.

For example, within CSCW there have been several attempts to develop mobile devices that have some of the portability of paper documents but also provide additional computational resources so that users have access to remote information resources and information can be displayed that is tailored to their local circumstances [e.g. 16, 1, 7]. Such technologies have the potential of offering quite novel ways of presenting, accessing and interacting with information. However, although mobile devices such as PDAs and tablets may be more portable than larger alternatives, the information displayed on them can often be hard to use within interactions in the local environment. Even when compared to paper alternatives such technologies do not seem to offer the capabilities for collaboration of more mundane paper documents.

The limited flexibility of mobile devices and screens have led researchers to look for alternative kinds of displays. Considerable attention is now being devoted to developing plastic substrates that are extremely thin and flexible. These have a "chromomorphic" component to affect changes in colour. This is normally achieved using an electric field or a small current, which is applied across the thickness of the display material. Several different chromomorphic systems are being developed. Gyricon [8], for example, has a sheet containing millions of bi-coloured microscopic spheres [5].

Each sphere has an electrical dipole moment so that it can rotate between the two colours when an electrostatic field is applied. E-Ink uses microspheres that contain dark and light particles with opposite charges that undergo electrophoretic movement in a field [6]. Other organisations are actually trying to print the electronics on the display sheet, possibly using conductive organic materials. This would enable thinner and more cost-effective displays to be produced [e.g. 19]. The Swedish company Acreo and NTera in Ireland [27, 37], on the other hand, use different types of electrochromic chemicals that change colour when they are charged. More recently are the electro-wetting surfaces patented by Philips [26], which enable coloured oils to cover or expose white surfaces under the influence of an electric field [30]. These devices all produce a two-colour display - often using blue and white - but with more complex electronics they are, in principle, capable of a full-colour output. Although prototypes of each of these technologies exist, few, if any, of these products have reached large-scale commercialisation.

These developments focus on the capabilities that paper has as a display, others have considered using paper as an input device. Familiar to researchers in CSCW are initiatives such as DigitalDesk at Xerox EuroPARC which use video-capture systems, whereby a camera above a desk is used to track the position of the pen and paper [34] or where a camera is placed above a pen to ‘capture’ images [2]. Using video-free technologies, such a SMARTBoards or graphics tablets (like the Cross Computing iPen) have enabled researchers to explore applications where marks, annotations and even handwriting can be transferred to the digital domain [23, 22]. More recently, devices have become commercially available that use ultrasonic triangulation to capture the motion of special pens on A4 pads, such as Seiko’s Ink Link, or Mimio for use on flip-charts. These can capture writing made on paper, and thereby begin to bridge the divide between the paper and electronic domains. However, these solutions typically require some external device such as a video camera, a graphics tablet, SMARTBoard, or an ultrasonic detector. Furthermore, the co-ordinate system used to detect positions, is set by the detector, rather than the paper,. This detracts from the portability and flexibility of paper. A more direct pen and paper paradigm would seem to be required to link the position of a pen on a writing surface.

One approach used by researchers is the use of some visible marks, the most familiar of which are barcodes. The familiarity of the mechanism and the common availability of barcode readers has meant that several researchers have explored simple applications where barcodes can link paper materials with electronic resources [15, 32]. More sophisticated methods are to encode linking information within locations on the paper. This may be by printing visible patterns such as Xerox glyphs or CyberCodes on a page and detecting these from cameras [18, 14, 36, 24] or some other reading device such as the emerging popularity of RFID tags [10]. Relying on barcodes or other visible marks does reveal the augmented functionality to the user but it can be quite disruptive to the displayed image and content. Perhaps a preferable approach would be to track the position of a pen or reader over the paper surface where the encoding is invisible, or if this is not possible, at least the pattern is not obtrusive.

One way of detecting positions on paper has been developed by Anoto [33] which forms the basis of commercially available products such as Nokia's Digital Pen, Logitech's io and Sony Ericsson's Chatpen. These devices capture handwriting so notes can be sent via e-mail or downloaded to a computer and then converted to text. The Anoto technology relies on an almost invisible pattern of pre-printed dots on the paper and sophisticated electronics built into the pen. Instead of scanning and recognising single lines of text, the Anoto pen uses a built-in CCD camera to view the infrared-absorbing dots, each of which is slightly misplaced from a square array. The relative positions of dots in a six-by-six array maps to a unique x-y position in a vast possible address space. Images are recorded and analysed in real time to give up to 100 x-y positions per second, which is fast enough and of sufficient resolution to capture a good representation of all handwriting. The equivalent of several A4 pages can be recorded and stored in the pen before being transmitted to a PC.

The Anoto technology offers one way of interlinking paper and digital resources. The developers of the technology recognise the pervasiveness of paper and seek ways of exploiting this to provide a novel interface into a digital world. To do this they have preserved the paper substrate, only making minor transformations to its colour. In a pad or on its own, the Anoto paper document is as flexible and as portable as any typical paper product. It can also be printed (and printed over) with conventional devices in the office environment. This technology does, however, focus on one particular activity associated with paper, that of writing. Trying to capture handwriting and then transmit it requires sophisticated technology – cameras, processors and mobile transmitters. This may be why the technology works in a certain way, for example, transmitting in batch, say once a page is completed, rather than as the handwriting is produced in real time. Although with Anoto the paper is not significantly transformed, the use of the Anoto pen, like most augmented devices, transforms the activity of writing. As well as requiring additional explicit activities of the user (e.g. ticking boxes when pages should be transmitted), in its current implementation, it requires users to consider when pages are complete and ‘done’.

The pervasiveness of paper and its undoubted capabilities for supporting everyday activities has led researchers to consider how to replicate these capabilities and in different ways bridge the divide between paper and the electronic. Each places different constraints on potential users. Some of these rely on other technologies being available, for example whether cameras are placed above a desk or page or detectors clamped across the top of a sheet. Others focus on paper more in terms of a display or and others as paper as an input device. They also may depend on how much conventional paper documents have to be visibly transformed in order for the technology to work. Others make more fine-grained transformations to the activities of potential users, requiring explicit actions by the users, explicit orderings of activities and involve conceptions of reading, writing and how the divide is bridged.

In this paper we will discuss a project called Paper++ that explores a different approach to augmenting paper. We commenced with what seemed the simplest way of interlinking paper and digital resources, just by pointing to paper documents. We aimed, at first, to focus on support for reading rather than writing. Drawing on our studies of paper use in a number of settings there seem to be times and circumstances when such support would be useful, particularly when pre-established texts are used alongside computer systems either by individuals or when individuals are collaborating with others. It seems there are possibilities where electronic resources could enhance reading and working with ordinary paper documents, which could draw from recent developments in hardware and electronics, in software infrastructures and from new approaches to designing multi-media materials. By commencing with consideration of a simple way of linking paper and electronic documents it may then be possible to develop understandings of how to support more complex interweavings between the two domains.

4. SPECIFYING AN AUGMENTED PAPER SOLUTION

The underlying technical approach taken by Paper++ is quite simple and is informed by the simple idea of linking paper with digital resources. As with Anoto, we use a paper substrate and utilise a non-obtrusive pattern on the page. However, we focus on the circumstances where users interact with pre-printed artwork on documents, where the paper could be a single sheet, a booklet, a pack, or a printed book.

As part of the project we undertook broad investigations into the interrelationships between paper and digital resources. As well as particular studies of paper use in educational settings, we carried out a number of 'simulation studies' with devices with many of the properties we were envisaging (e.g. using bar codes and using commercially available non-obtrusive pattern detection). These allowed us to explore some of the design challenges of the new technology prior to any integrated hardware solution being available. They also served as demonstrators we could use when presenting the project to potential collaborators, resources for the conceptual designs we developed and as concrete materials to discuss in our studies of potential content providers of augmented paper solutions [21].

Coupled with our previous studies of the uses of paper and specific studies of educational settings, these activities suggested some preliminary requirements for the overall Paper++ solution. For example, studies of the mobility of paper in interaction suggested properties that were required of the paper substrate. It is apparent that more than one individual would need to read, and in other ways use, the same document at the same time. This suggested the kind of reading angles and visibility required of the paper document, the kinds of flexibility required, how roughly paper could be handled, and the kinds of actions performed on paper by pens and other devices. To be mobile not only would the paper have to be light and mobile it needed to be *malleable*. So for example it could be bended in order for one reader of a booklet to see a lower page whilst another read the page before it. The paper would also have to be *moveable* across a surface, as in the case when an individual's single finger is used to slide a piece of paper across a desk to make a feature on it apparent to another. The augmentation should not degrade this mobility. We should not attach anything to the paper or force its placement under of above another device, restrict its orientation or unduly increase its friction over other surfaces. We should not constrain the *visibility* of the paper, so we could not greatly transform the surface of the substrate, nor its *flexibility* – the substrate would have to be as foldable and manipulable as a conventional paper or thin card product – nor its *robustness* – the coding would have to be as permanent as the rest of the artwork and should not be degraded by the use of the reader. Indeed, the coding and artwork would have to be persistent after use. The action of the pen should not itself impede the readability of the code. Any coding or coating should be resistant to wear. The coding could not 'break' or in other ways deteriorate if bent (and also should have minimal degradation if folded).

Our observational studies also suggested some less definite criteria. For example, for the sake of application and media design we preferred not to identify any particular part of a page as one that should be encoded (or not). Given the potentially wide range of uses or applications we should not constrain how parts of a page should be used, particularly if we wanted to have the possibility of two individuals using the document at the same time. Hence, the whole surface of the paper would have to be uniformly encoded and have the potential of being 'active'. Unlike barcodes which encode information about a link directly, the Paper++ solution would require only indirect encoding of locations, the associated information, link and 'response' being defined by the software and could possibly changed 'on the fly'.

These requirements placed a great constraint on the hardware design, and also had consequences for other components in the technical chain.

5. THE PAPER++ APPROACH

The approach we took in Paper++ was to develop a cheap and simple pen-like device that can relate paper materials to digital content. Printed documents would be overprinted with a non-obtrusive pattern that uniquely encodes the x-y (and page) location on the document. This code could then be interpreted by a pen when it comes in contact with the paper. The pen needs to convert the code into a signal that can be an input to a PC, or another digital device. When a location is selected then, supported by a software infrastructure, an appropriate action in the digital domain can be initiated – this could be playing a sound, the display of some text or web page or activating a video clip of some animation. The paper, then operates like a touch-screen, only encoding information about location, all other relationships can be defined through software by a content provider. This should be easier to update or tailor for particular users. Given a pre-printed paper product, like a text book, one could envisage applications where updates, additional resources and customised information is provided in the digital domain. Obviously the approach relies on some way of establishing a relationship between the paper and the electronic.

As with the approach adopted by Anoto the Paper++ solution relies on a non-obtrusive pattern, but the process for this is quite different. Rather than using a pattern that would be detected optically we use inks that can be detected conductively. Conductive inks have been developed that have electrical properties which have been used in some security applications (e.g. banknotes) and more notably for reducing static on films where the inks used had to be transparent. It seemed feasible that sophisticated invisible and conductive inks may serve as a foundation for a simple way of encoding non-obtrusive patterns on paper. A detector could be developed requiring just two electrodes that could convert the code into a frequency-modulated signal. This solution also has the potential of being very cheap.

This choice implies challenges that differ in some ways from many recent attempts at developing ubiquitous or augmented applications, particularly those undertaken within HCI and

CSCW. The foundations to the approach require technological developments in a number of diverse disciplines: organic chemistry for the inks, electronics for the pen, signal processing and mathematics for the encoding and information architectures for the software infrastructure. The technical choice means that there were few components commercially available that we could integrate. The technical challenges of identifying an appropriate conductive ink and paper combination, designing an encoding pattern and developing a robust reader were considerable. These would be critical challenges for the project.

6. THE HARDWARE SOLUTION

In trying to preserve the features of paper that afford collaboration, the Paper++ project chose to try and maintain the use of a conventional mass-produced paper product. The principal hardware innovation would then be the use of conductive inks.

The development of conductive ink draws on innovations in conductive polymers in the 1970s. These were developed for quite different purposes principally for coating films and screens to reduce static [4]. Initial experiments showed that it was possible to print a conductive polymer called Pedot (Poly(3 4)-ethylenedioxythiophene) invisibly on a thin film. Although having good conductive properties, this solution was not robust and failed abrasion tests. It requires another coating (or substrate) and thus transforms the flexibility of the material or reduces the visibility of any printed artwork. We could print a Pedot pattern on paper. This was conductive. Unfortunately this was highly visible and appeared dark blue in colour. It was apparent that even given the wide range of paper substrates available with different surface characteristics and weights, printing on any paper was considerably different than printing on a film substrate. With the help of a printing research laboratory in Sweden (Acreo AB) we did manage to produce a conductive ink pattern on a conventional paper product where the pattern did not obtrude through the artwork. This used a variant of Pedot (PEDOT/PSS: Polyethylendioxothiophene/ PolystyreneSulfoniumSalt). This is also resistant to abrasion, shows the required conductivity and has kept its electrical properties in environmental testing. Producing a solution that works on paper also required considerable experimentation and innovation into the ways the ink is deposited on paper. This involved exploring processes that printed the pattern both over and under the artwork and other solutions drawing upon the irregular properties of the inks when they are printed on paper.

For the solution to work it would be necessary to detect at least one level of conductivity from the pattern. As we are endeavouring to produce a simple reader we need a significant difference between this level of conductivity and the base level conductivity of ordinary paper.

In association with the development of a conductive ink we designed a pattern to encode locations. This design had to be considered in relation to the kind of detector we needed to pick up signals from the ink and transform these into locations. At the commencement of the project we did not wish to specify whether this would be detected by a swiping action or a pointing (or placing) action. We had the added difficulty that as the pattern would be barely visible (or invisible) we could not rely on users placing the reader in the correct position over a location or swiping between two points (i.e. the ways barcodes are read). We designed a pattern that would be robust for the different reading schemes, that could encode at quite a large resolution and where it would not matter where the user started the action. The encoding scheme we developed is based on a Manchester coding scheme but draws on the conception of barcodes by coding locations as vertical lines of conductive ink across the page.

In the early stages of the project we investigated a number of ways of detecting the pattern, including a comb reader with a large number of points of contact that could detect signals by being held in one place, and a swipe wand that was operated through a short movement. Although there were advantages and disadvantages with each, it emerged that the swiping approach was the more flexible and robust solution. It may also be noted that for most activities of users there would be some movement of the pen. Nevertheless the pen would have to be designed so that it could be held in either hand in any orientation and might be quite roughly handled. As the inks are conductive, only a simple reading device is really needed. For example, initial nibs were adapted versions of conventional brass fountain pens with the nib split to provide the two points of contact. To overcome undue abrasion on the surface different arrangements of the two points were developed. The current nib has a concentric design, one electrode surrounding the other. In appearance it appears similar to a large highlighter pen with a ballpoint nib. In operation the central electrode is similar to those found in electrical test equipment or in some printers (see Figure 1).

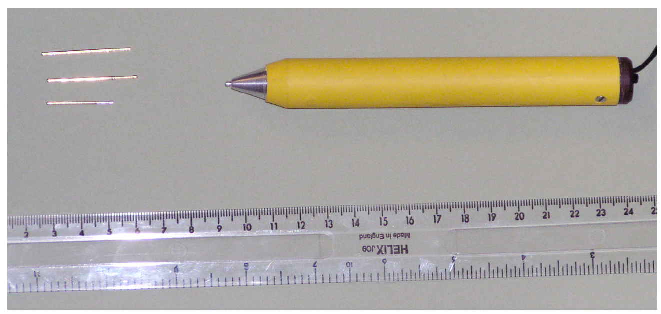

Figure 1: The co-axial pen with 3 optional nibs (left). Below a ruler provides an indication of scale .

As can be seen, efforts to augment paper to support a simple link between paper and electronic resources requires extensive work, knowledge and expertise in organic chemistry, paper and printing, electronic design, mathematics and system integration. This is just to provide a ‘proof of concept’ that could detect electronic signals. This would have to be converted to location information and transmitted to a computer. As with the rest of the system, it was decided to start with the simple approach – producing signals that could be decoded by a soundcard.

7. THE SOFTWARE SOLUTION

In our studies with simulations of the Paper++ approach it became apparent that preserving many of the qualities of paper not only presents problems for those augmenting the material devices, but also for those designing the information and managing it. One of the critical advantages of paper is that it is portable and mobile and can be used in a wide range of locations, almost anywhere. Paper++ aims to preserve this mobility and enhance it so that when individuals are close to computational resources they can make use of this proximity to augment the documents they have with them. This means that for a Paper++ approach to be feasible paper documents should both be used on their own and with electronic resources. Hence, designers of augmented documents have to design standalone documents and make any additional functionality apparent and attractive. Initial experimental designs with interactive textbooks showed the approach was feasible, but great care needed to be taken over the design of the materials in each domain. Each media had to be carefully matched to the resources through which it was made available. For example, video, audio, animations and other moving media, recent information and activities like interactive question-answering were useful augmentations. However, it could be unclear why other items like additional linked text should be presented in the electronic domain, particularly as there are familiar textual and graphical conventions for making these easy to see and notice on paper. Augmenting paper then requires careful consideration of the kinds of applications it can be used for, and the ways in which information can be designed and managed that are appropriate for those applications.

For many applications linking paper and electronic resources can be quite simple. It is easy to envisage a straightforward linking mechanism that ties locations generated from the pen-paper interface to simple actions. This could be accomplished in much the same way as links on web pages, for example tying a paper resource to a particular document and application so that audio, video and animation files could easily be invoked in the electronic domain. A designer could then just associate locations on the paper pages with particular electronic resources when required. These could be updated and amended when required. It could also be straightforward to develop authoring tools to support the creation of such links.

This was an approach we undertook in the initial phases of Paper++. However, this simple model provides only a one-to-one correspondence between locations on a page and electronic resources. There are applications where it may be useful for different actions to be invoked depending on the context of use. Responses by the system could depend, for example, on the particular user or on other actions the user has previously accomplished. Although the pattern is printed on the page it does not have to be tied to fixed actions or indeed simple shapes. As well as allowing for flexibility in the objects that are linked together we could also could allow flexible ways of managing the links. There could be applications where links could be generated on the fly or produced in some form of collaborative activity amongst users.

In order to allow for the possibility of more general and flexible solutions we developed an open hypermedia system, called iServer, based on a generic cross-media link framework [25]. Specific media types can be integrated through a plug-in mechanism as indicated in Figure 2 which shows the main components of the iServer core and those of the plug-in developed for Paper++.

Links are first-class objects which can have any number of sources and targets. By introducing a general concept of entities that may be sources or targets of links and then making links a subset of entities, we achieve full generality of allowing links to any types of entity, including links themselves. We further classify entities into the subsets: resources and selectors. Resources represent entire information resources such as media files, web pages, databases etc. Selectors specify elements within resources and provide a means of linking to and from parts of resources as well as entire resources. For example, in the case of web pages, a selector could be an XPointer expression.

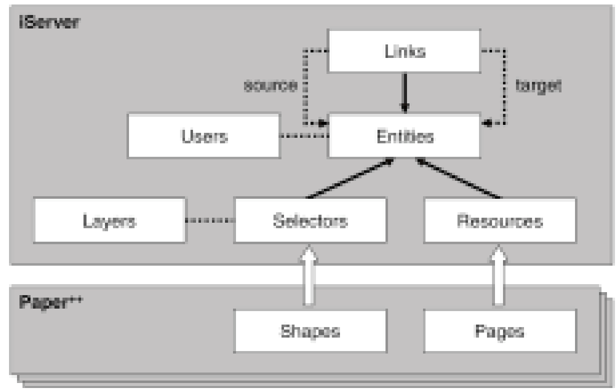

Figure 2: Generic Cross-Media Link Server

The plug-in for a specific media type must provide implementations for selectors and resources. In the case of Paper++, selectors are active areas within a page defined by arbitrarily complex shapes and resources are pages. To date, we have also developed plug-ins for XHTML, images, audio and video.

The iServer framework has been implemented using the OMS database management system developed at ETH Zurich [17]. In OMS, both data and metadata are represented as objects and handled uniformly. By using expressions of the OMS query language (AQL) as selectors on OMS database resources, we are also able to create links to and from objects of a database where these objects may either represent application concepts (metadata) or instances of those concepts (data). In other words, if we had the word ‘cat’ in a printed document, we could create a link to a database object that represents the type ‘cat’ or to an object that represents a specific cat.

The approach that we have taken provides us with a very flexible means of integrating printed information with digital information. We can dynamically map not only document positions to information objects but also information objects to documents positions and it is therefore possible to find references to digital objects within a collection of paper documents. The infrastructure also supports the layering of information in different ways, allowing single points on the paper surface to be related to different kinds of resources [31]. A resource may have any number of virtual layers and a selector is associated with exactly one layer. Layers are ordered and may be re-ordered, activated and deactivated dynamically by the application.

A user management component is also integrated into the iServer core and in combination with the layering mechanism this offers the potential for link activation to depend on a whole range of factors such as the role of the users or their previous actions, even those made over the same location (as in the case of zooming through repeated selections). This is just one of many possibilities that require further investigation and exploration in order to see whether and how they could be used to support the bridge between paper and digital resources. For example, it is possible to link any kind of resource, including links back to the paper domain, it is possible to create links dynamically and it is possible to manipulate link information itself as a resource. These capabilities could support applications, which require the transfer and sharing of links. These capabilities may not be just important when considering novel augmented paper applications but when the infrastructure is used to support the development of authoring tools.

The software architecture had to make possible both fixed and dynamic linking of information within and between materials, in both the electronic and digital domains. It also needed to support different ways of providing content. For these requirements to be met, the information infrastructure has to be built upon a set of clear concepts that allows for different kinds of authoring of materials and different ways designers and publishers to link these together.

The most straightforward way of considering the authoring of links was to provide a tool to support the creation of links between existing content elements. The tool we have developed supports any kind of shape and multi-layer authoring for complex figures. Further, it enables the authoring of multi-user documents that contain anchors (shapes) linking to different resources determined by the user currently working with the document. Figure 3 shows a screen shot of the authoring tool.

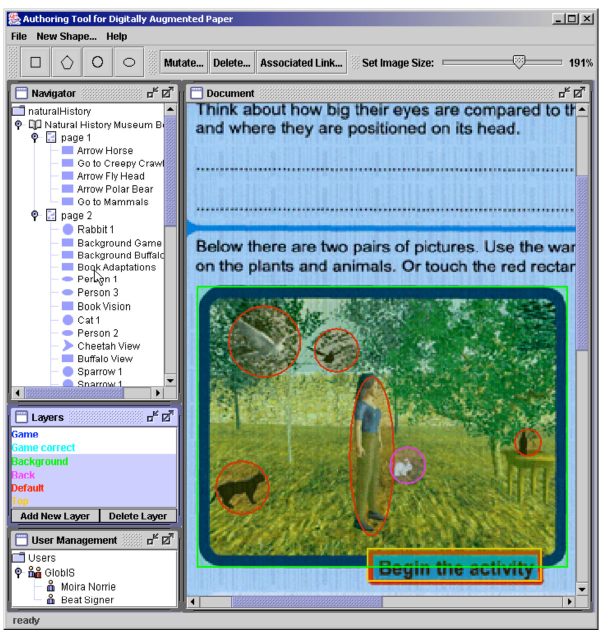

Figure 3: The authoring tool using material developed by the project. It is also possible to see the positions of the coding scheme in the figure (right hand window)

In order to consider the integration of the various hardware components with the software infrastructure and to assess our initial concepts of linking and authoring, we developed an integrated demonstrator in Paper++. Keeping to our theme of educational settings this was undertaken in the domain of museums. In collaboration with the Natural History Museum London (NHM), we designed an augmented paper worksheet for use in various galleries in the museum, including more focused activities which would take place in the new exploratory 'Investigate' area sited in the lower floor of the museum. It was envisaged that the primary audience for the worksheet would be children aged between the ages of 9 and 14. They would use the worksheet in various locations around the museum, but in the Investigate area there would be a dedicated computer systems where they could bring up associated computational resources using the Paper++ pen.

8. AN INTEGRATED DEMONSTRATOR

In discussion with the NHM's educators and designers the focus for the worksheet was decided to be animal vision. The collaboration involved designing the worksheet, developing the interactive components and also assembling the digital materials. Active areas, reflected in the design by areas being boxed allowed for related images to be displayed (e.g. from associated galleries in the museums), sounds to be played, an animation being invoked (showing the differences between insect and human vision), videos being played showing relevant animals in their environment and additional textual information giving examples and related concepts. Some actions on the page invoked activities that could be explored further on the computer. For example, electronic magnifications of fly's eyes could be zoomed into using the computer system. We also designed an interactive capability through which children could actively explore different kinds of animal vision. In one mode this would provide related information about the objects selected, in another (the 'game' mode) the users would undertake an activity to check their understanding of the concepts explored so far. This interactive element required the use of complex shapes defined by the designer, and, in a simple way, the use of multiple layers. The responses (aural or visual devices) depended on the previous actions undertaken by the user on the sheet. We used the authoring tool to assemble the digital content and develop the links with the paper sheet.

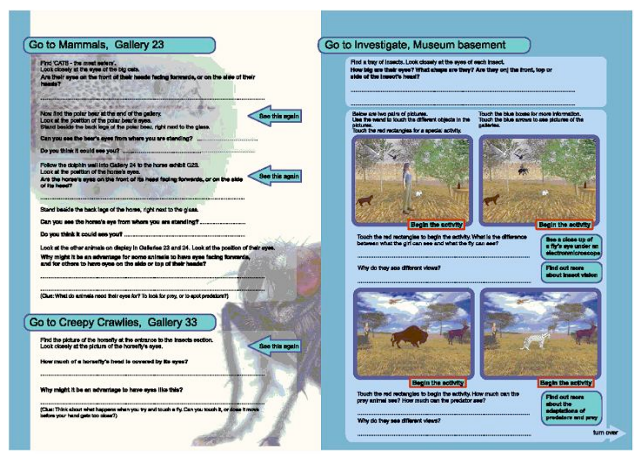

Figure 4: The central 'active' pages of the worksheet. Layers are invoked by activating the pictures on the right hand side.

The worksheet is a two-sided page (European A3 in size, but folded to A4 in Portrait format), one of the sides having the conductive pattern. The worksheet is printed on a thick (card-like) paper (250 g/m2) for ease of use around the museum (see Figure 4). The participants used the co-axial pen developed in the project to activate the worksheet, the results presented via a computer system on a flat screen. They also had a keyboard and mouse through which they could explore the electronic domain if it became appropriate.

The principal achievement of the trial was the production and demonstration of a complete chain of the technology involving participation from 7 organisations and collaboration between museum professionals, educators, social scientists, designers, engineers, chemists and computer scientists. Over 20 users (aged 9–14) tried the Paper++ technology as well as numerous museum professionals, educators, parents, teachers and other members of the general public. All considered this to be a technology that could enhance visits to the museum, including general visits and those undertaken by school groups. Although the code is visible, from the recordings we made of the users carrying out the task, it did not seem to detract from the artwork or seem obtrusive. Indeed many thought the coding was part of the design. The sheet could be used in many locations with varied lighting conditions in the museum. Children read and wrote on it whilst supported in their hands, on their knee, by cabinets and in relation to different features of the environment (see Figure 5). As expected the sheet, when either open or folded, was a resource for collaboration between two or three participants. Groups of two or three could read the document together in a variety of orientations, one could read and another write, or when on a flat surface two could write and/or draw at the same time. Moreover, the design of the worksheet and the configuration of the pen also meant that users seemed to have little difficulty understanding the technology and how it was meant to work.

Figure 5: **the use of worksheet in the mammals gallery of the Natural History Museum (above) in the laboratory space of the Investigate area (below). Swiping a location (left bottom) and viewing the response (right bottom)**

However, despite the concept being clear the technology is still at too preliminary a stage to be assessed in any detail with respect to its use. Despite laboratory experiments showing a ‘hit-rate’ of 80%-90%, in a museum setting the rate was much lower (nearer 20%). Technical investigations pointed to a number of explanations for this including the choice of the paper (being a Xerox paper it had too much salt), the printing of the associated content on the covers of the book (a laser process possibly transforming the conductivity of the paper) and the humidity of the basement room in the museum. The demonstration provided evidence that such an approach was feasible and that elements of the technical chain could be integrated. It also provided an invaluable resource (both in situ and via recordings) for presenting the Paper++ concept to diverse audiences. However, it did not provide extensive materials suitable for assessing the usability of the application.

The trial has engendered a number of technical activities to be undertaken, including investigation of different printing processes, consideration of other factors in the choice of papers and inks and a re-design of the circuitry and nib of the pen Thus, members of the Paper++ project have continued this approach to developing an augmented paper solution. However, undertaking such a technical intervention has raised critical issues regarding our understanding of the paper, not only in terms of how it is and could be used, but also how augmenting it can require a fundamental reconsideration of its properties and the processes that surround it.

9. DISCUSSION

Paper++ reflects the growing commitment in CSCW and elsewhere to augment everyday artefacts with associated computational resources. Unfortunately, however, there are no commercially available products that can adequately preserve the integrity of conventional paper whilst enabling complex and systematic links to digital materials. Other solutions largely focus on enhancing writing or have to radically transform the material qualities and characteristics of paper. Although, the project focused on exploring different applications in varied educational domain, the technology could be applied to numerous other settings associated with either work or domestic settings.

The distinctive character of the technology is in allowing associations to be made between printed materials and electronic resources. So one could envisage applications where it is necessary to associate medical texts are electronic resources. These could be standard documents or bespoke materials produced by professionals, practitioners or even patients. Such materials could provide a resource for discussion or less focused collaboration. Or, one could envisage the production of augmented paper materials for the design professions, particularly in cases where additional computational resources can support different ways of interacting with texts and diagrams, for example in showing details, other forms of visualisations or calculations. Or, such augmented paper resources could be part of more general applications where printouts can be associated with computer materials. Again, such possibilities could support the numerous occasions when participants, either on their own or in collaboration with others, need to create affinities between printed paper and electronic information.

However, in developing an augmented paper solution it became increasingly apparent that in attempting to enhance this conventional artefact, we needed to rethink and reconsider a long-standing and well-known process, namely printing inks on paper. Over the centuries printers have progressively refined the process to enable inks to provide quick drying, clear images. Paper is optimised to give good wear resistance and strong visual effect. The refractive index creates considerable light scattering that gives inks added clarity. Printers describe this as “snap”, and the paper as having low ‘holdout’. These qualities are enhanced by giving paper a rough porous surface at the micron scale; papers with high holdout tend to produce very poor printed images. To successfully print conductive inks we require very different qualities. We need to lay down a continuous, transparent film over the printed area; a film that requires a smooth surface with high holdout. The requirements for the continuity of the film and the invisibility of the layer stand in strong contrast to the aims of conventional image printing. This has led us to radically reconsider the printing approaches by which we lay down conductive patterns on the page.

Our initial conception of how the paper and digital could be interrelated was by simple linking – an action on a page invoking related responses via a computer system. Nevertheless, this seemingly simple relationship between the paper and digital resources involved considerable effort to produce the limited materials for the trial. This included identifying, collecting, re-editing and re-segmenting existing materials, collecting new materials and assembling these together in a coherent design. We were informed that conventional activity sheets designed by the museum typically undergo around 10 iterations of design and assessment. However, even in our single iteration it was apparent that an augmented paper solution adds additional complexity for the work of content providers.

This reflects the findings from our studies of content providers, both of conventional publishers and of multi- or cross-media publishers [21]. These revealed that many conventional publishers (of educational text books, for example) are wary of new electronic means of production. This is partly due to previous problems they have had when developing related CD-ROMs, Web and eBook materials. It is also in part because of the extensive work required to author content, even when this is available and not subject to copyright or other license arrangements. Those publishers who already produce across different media have related concerns. In order to design integrated augmented paper solutions it seems necessary that at best some redesign of the content is necessary. Even in the case of video fragments, a technology like Paper++ seems to require considerable transformation. In the least it seems to require editing for clips of a shorter durations and more care that these clips when invoked are coherent with the associated paper electronic materials. From our experiments it is apparent that it may not be straightforward to transform such materials simply by trimming. It is more likely that there would have to be significant alterations to the original content and the way these materials are gathered. It may require, for example, when content is gathered a number of different versions to be collected, where some are more appropriate for particular media or combinations of media. This is additional authoring work to that required to produce the links.

We therefore need to consider the support for publishers necessary to facilitate how they can author their own links and re-consider the activity of linking text and digital materials together. As with many technologies that seek to augment existing media, the potential of re-use of existing content may not be so great as first hoped.

The explicit authoring of links can be time-consuming and it may be that sophisticated tools are required not just to support the authoring of content, but also of links, perhaps even to support the dynamic production of links. It may be that models of the process of authoring links could be reconsidered. Rather than this being the sole responsibility of a publisher or a designer, these may be produced by 'users', for example, commencing from a simple foundation, more links may emerge through authoring by communities of users, and making use of existing links by others in other media. Indeed, it may be that publishers may not be the only, or most suitable, providers of content for augmented paper solutions. There may also be applications of augmented paper for bespoke publishers. Even in educational settings there are already individuals who have the responsibility for assembling content for ad hoc publications or packages of content, whether these are curators, educationalists, teachers, parents or even school groups. If users can author their own links, then through a more open link authoring scheme users could produce their own links and not only those provided by a single publisher. Clearly, the ability to freely create links between arbitrary printed materials implies a major shift in the consideration of augmented paper. Such capabilities require a sophisticated information infrastructure that can manage emerging links and interconnections in a coherent way. Perhaps unusually in CSCW this has required drawing on expertise in database design and required significant innovations in database architectures. It also requires detailed consideration of the needs, resources and practices of various 'content providers' rather than just on the usual focus on 'end users.'

Although the concept of augmenting reading seems simple and straightforward, and users and others seem quickly to understand how the technology may work and what additional functionality it could provide, augmenting a pervasive and resilient artefact may not be enough. We need also to consider the requirements and demands of others in the production of such a solution, particularly those which have to produce and transform content for augmented technologies.

This perhaps is most apparent when augmenting paper technologies, particularly those to support reading. When developing these, it is perhaps inevitable that developers cannot rely on just being able to link the physical objects together and appropriate actions emerge. Inscribed on the paper document are a great variety of elements. There may be conventions for how they are presented, but the interrelationships between these elements are complex, particularly if we consider how these documents are read in practice. Bringing together the uses of paper and electronic resources, as in many other ubiquitous computer initiatives, cast these complexities into sharp focus. In a large number of settings we can observe the practices of participants as they interweave their uses of paper documents with digital ones. Indeed, it is possible to identify problems and difficulties participants have in trying to do this. It therefore seems to be a domain where augmentation maybe potentially appropriate. However, what becomes apparent through investigating one way of doing this, is how little is understood about how participants interweave these resources, the objects and elements they find relevant for particular activities, how these are identified and assembled as collections, and how they are juxtaposed with other resources – how participants create affinities across different materials. Notwithstanding the wide ranging research in CSCW that powerfully delineates the significance of paper to work, communication and collaboration, when we draw on these to inform the design and development of a seemingly simply solution, we find how little we know about the practical use of paper in naturally occurring environments. Indeed, our studies have only begun to touch the surface and our solutions are far from robust and yet bridging the paper digital divide should we believe at the heart of agenda of CSCW

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