Augmented Paper: Developing Relationships between Digital Content and Paper

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1. INTRODUCTION

Some of the most interesting developments within computer system design in recent years have emerged from an exploration of the ways everyday objects and artefacts can be augmented with computational resources. Often under the rubric of “ubiquitous computing” 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 computing ‘solutions’. These developments mark an important shift in system design, a shift that is having a corresponding impact on social science research. Surprisingly though, given the growing commitment to the ubiquitous and the tangible, there is a mundane, even humble artefact that pervades our ordinary lives that has received less attention than one might imagine. This artefact is paper.

In this chapter, we discuss a solution that enables people to create dynamic associations between paper and digital resources. The solution does not rest upon replacing paper with technology, nor with transforming the character of paper, but rather with augmenting paper to support systematic links with digital content. Our approach was not primarily concerned with the capture and enhancement of writing and note-taking (as with other developments), but rather was primarily concerned with reading, and enabling people to access, or create connections between paper documents and digital resources. As an example, consider how one might link an educational book with a television series. Such a book could be augmented to enable the reader to point to pictures or text on the page and instantly view associated video clips on a workstation, a PDA or television set. Pointing to the paper document might also allow readers to access and play interactive games, listen to associated audio clips or seek out other kinds of related information.

In this chapter, we discuss the three year development of an augmented paper solution as part of “Paper ++”, a pan-European project funded by the Disappearing Computer Programme. This project focused on the potential for augmented paper within a particular broad domain – learning environments – ranging from more ‘formal’ educational settings such as classrooms through to more ‘informal’ settings such as museums and galleries. We discuss the emergence of a technical system and the ways in which it resonates with observations and findings from empirical research, both our own and studies by others [21, 12, 13, 35, 9, 30]. 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 through a series of empirical studies, simulation studies and conceptual design exercises. Finally, we describe a ‘naturalistic experiment’ in which school children used the solution during their visit to a museum. In the course of this project, 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 of the development of augmented everyday objects.

2. BACKGROUND AND REQUIREMENTS

One of the developments within areas such as Human-Computer Interaction (HCI) and Computer-Supported Collaborative Work (CSCW) has been the emergence of a substantial body of naturalistic research concerned with human conduct, communication and collaboration in everyday settings. These studies have provided empirical findings that have allowed us to reconsider and even re-specify many of the more traditional ideas concerning the ways in which tools and technologies, objects and artefacts feature in action and interaction [e.g. 29, 3]. Many of our 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, 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 [35]; and so on. The significance and purpose of paper within these domains and many others has been drawn together in Sellen and Harper's book - The Myth of the Paperless Office [30].

In the rest of this section we review how and why paper has remained so resilient and useful as a resource for information and collaboration, alongside newer digital technologies. This draws on insights from a number of observational studies of reading off paper and screen conducted within the project, in educational settings as well as on previously published studies. We do this in order to identify requirements for augmenting the functionality of paper in an environment where paper and digital resources co-exist.

The affordances of paper

In schools, colleges and universities we also find the persistence of paper. In schools, for example, papers and books are taken home for homework, books and worksheets are taken to the teacher to be marked, and paper materials are used as the focus for discussion. Similarly in museums and science centres, paper provides resources for visitors throughout their visit around the setiing. These materials range from simple brochures and maps through to catalogues that provide detailed information concerning particular exhibits. Amongst many other activities, such resources allow visitors to carry the information to particular exhibits and delicately juxtapose reading the document with inspection of the exhibit.

It is clear that one of the reasons paper excels in these roles is because it is easily maneuvered. However, we can see that it is not just that paper is easy to carry around, or easy to pass from one person to another, but it also affords tiny shifts in position or orientation, which plays a vital role both in configuring materials for the activity at hand, and also in directing attention in collaborative activities – a property we have previously characterised as 'micro-mobility' [21].

Previous studies in a number of workplaces have also highlighted how the flexible nature of paper supports a range of activities. For example, the discrete and lightweight properties of paper mean that it can easily be passed around in an office environment, and also moved in the local area of a desk, for example to configure related sets of documents for a particular activity [21]. Furthermore, individual papers can be literally flexed for example, when comparing information on one part of a page to another. The ability to lay information out in space using paper has also been found to be of vital importance in many key kinds of reading activities [30].

These properties not only support the individual but also support the way in which participants collaborate over documents together. In an example taken from one of our studies, two children (Figure 1) are using an encyclopaedia to find out information about a particular animal. They use the book together, bending the pages enabling them to undertake distinct but related activities with the book. For example, one child can look at one part of the book whilst the other is reading an earlier section, bending the page of the book to get a better angle to view the page. The children also can mark out particular areas in the book when they are both viewing the same page, for example by placing their hands or fingers in the book as the pages bend around them.

Fig. 1. Two children manipulating a book at the same time.

The mobility of paper also supports collaboration. For example in reading, a document can be tilted towards the reader or a document can be slid across the desk for another participant to see. The maneuverability of paper can also support transitions between different kinds of collaborative activity. Paper is often shifted or moved to encourage participation or invite a response from another person by, for example, rotating or sliding the paper to provide the other person with better access. There are many ways, therefore, we see children make use of the properties of paper to support delicate shifts in orientation and access to materials at hand. In developing augmented paper, it was a goal of the project to ensure that such properties could be preserved as much as possible.

Embodied writing

Paper is rarely used in isolation from other artefacts. Most often it is used as part of a collection of various paper documents, writing devices, and other information sources, even digital displays.

Pens are probably the most obvious common implements that we see used in conjunction with paper. But pens are not just used for writing, they are often used to point, delineate, and mark items or pages. However, from our empirical materials, it is apparent that writing is an embodied activity that involves more than the fingers of the writing hand holding the pen. Indeed it often requires the whole of the body and may involve the second hand to steady the paper as the writing takes place. Further, writing, and the ways in which it is produced, can also be as a resource for collaborative activities. In the course of writing, boundaries or junctures in the writing activity are visible to others. The position and orientation of a pen can be used as a resource to assess the current activity of the writer. From whether it is raised above the page, held above an item, or moved down to the edge of page, the activity of writing can serve as a resource for assessing the ongoing activities of another person. Moreover, the position of the pen in relation to the geography of the page allows one to determine another person's location within an activity. This can then be a resource for others to coordinate their own activities.

All of this points to the fact that in addition to paying careful attention to the particular affordances of paper within our domains of interest, so too do we need to consider the details of the activities within these contexts. Writing, and more particularly the use of pens, can be seen to be a key part of the activities with which we are concerned. Therefore we have to consider how the design of the system can be sensitive to how paper is used in combination with other mundane artefacts like pens and pencils.

Interrelating paper and digital displays

Novel augmented paper technologies may provide quite innovative resources for relating paper and digital materials. However, it should not be overlooked that in a number of domains, particularly educational settings, paper is already commonly used alongside electronic materials and devices. Examples include using a computer to search for information that is then written into a paper document, or, transferring and comparing information across documents.

One typical, difficulty faced by people we observed in school settings is actually physically getting both paper and digital sources close enough together to be able to interrelate information from one to the other, as illustrated in Figure 2. Here, two children are in the classroom working with a CD-ROM and a book (which comes with the CD). In this example, the boy has to move the book around for the different activities involved. It is awkward for him to position the book so that he can, for example, look from the information on the screen to information in the book, discuss the information with the girl next to him, and type in answers using the book. The book has to be positioned not only so the girl with whom he is working can see it, but also in relation to the other artifacts he needs in order to complete the task (i.e. the monitor and the keyboard). It is hard to configure the computer technology and the book in the environment to support collaboration between the participants.

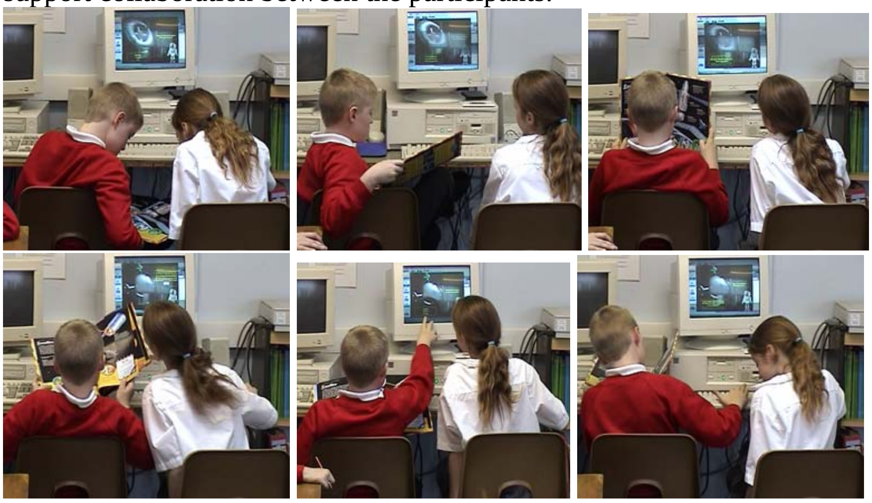


Fig. 2. Children in a classroom using a conventional book alongside a computer which presents related materials.

The foregoing observations may seem quite mundane, focusing as they do on slight movements of paper across the desk, the turning of a page, the holding of a pen or efforts to see how a paper print-out relates to its computer-based counterpart. However, these kinds of properties are critical to how activities are accomplished from moment-to-moment in interactions with others. Studies of the domestic environment, classrooms, museums and galleries and the like, reveal many examples of how paper is used within and alongside digital technologies. 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 other pieces of paper, and booking clerks labouriously write down the details of travel arrangements before trying to enter the information into a system.

All of this shows that 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. Surprisingly, not only has this fact been under-explored as a topic of research, relatively little effort has been devoted to trying to enhance the relationship between paper and the digital realm.

Requirements

Coupled with our previous studies of the uses of paper and specific studies of educational settings, these new insights suggested some preliminary requirements for the overall Paper++ solution.

At the highest level, the co-existence of paper and digital technologies, and especially the pervasiveness of reading off screen and paper together, reveals both the value and limitations of each media form. Paper is useful for information and collaboration, but is no longer sufficient alone. Digital information already supplements paper-based information, but has not replaced it. This leads us to the obvious conclusion of connecting paper and digital resources in more intimate ways, to support and extend the kind of movements people are already making between them. We have described this approach as augmenting paper with digital resources, but it can also be viewed the other way round, as augmenting digital artefacts with paper resources.

Furthermore, studies of the mobility of paper in interaction pointed toward properties that are required of an augmented paper substrate. It was 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, but it would also need to be malleable. Following on from this, it was important that any augmentation would not interfere or degrade this mobility. For example, this implied not attaching anything to the paper or forcing its placement under or above other devices, restricting its orientation or unduly increasing its friction over other surfaces.

Our observational studies also suggested some less definite criteria. For example, for the sake of application and media design we preferred not to pre-define the way that the design of a paper document should be linked to digital resources. Given the potentially wide range of uses or applications, and the legacy of existing documents in these settings, we did not want to constrain how parts of a page should be used. Hence, we decided that we wanted the whole surface of the paper to have the potential of being 'active'. Unlike other approaches (such as barcodes which encode information about a link directly), we decided the Paper++ solution should require only indirect encoding of locations, the associated information, link and 'response' being defined by the software.

3. INTERRELATING PAPERWORK AND SCREENWORK

Previous approaches

A number of researchers in ubiquitous computing have developed their own technological solutions to exploit or capture some of the affordances of paper. Some have tried to replicate some of the paper document's capabilities, for example by making applications more portable or mobile. These include *electronic books* which provide searchable, dynamic or multimedia texts, as well as *context-sensitive appliances* which adjust media content in response to other triggers in the environment [e.g. 16, 1, 7]. The limited flexibility of mobile devices and screens have led other researchers to look for alternative kinds of displays. Considerable attention is now being devoted to developing *plastic displays* that are extremely thin and flexible, and offer paper-like viewing experiences [eg. 8, 5, 6, 19, 28, 38, 27, 31]. However, none of the above technologies is even close to being as cheap as paper; so they are competing with LCD technology rather than with paper [15]. They also tend to overlook the interaction between electronic material or appliances and paper itself.

Other approaches have considered using paper as an input device. For example, the *DigitalDesk* used video-capture, where a camera above a desk was used to track the position of the pen and paper [35] or where a camera was placed above a pen to 'capture' images [2]. Other approaches such as SMARTBoards or graphics tablets (like the Cross Computing iPen) have used alternative techniques to capture marks, annotations and even handwriting to be transferred to the digital domain [23, 24]. A device that uses a similar approach to that is Paper++ is the "LeapPad", a robust touch sensitive tablet on which paper books are overlaid. Designed for children, the LeapPad is now a highly successful educational product, but relies on a substantial casing to hold the paper books.

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. While these techniques begin to bridge the divide between the paper and electronic domains, all of these solutions typically require some external device to detect interaction, detracting 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 [15].

Another approach has been to link paper and digital materials through the use of visible marks on paper, the most familiar of which are barcodes [15, 33]. More sophisticated methods 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, 37, 25] 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 of the look and layout of the paper document.

Alternative approaches track the position of a pen or reader over the paper surface using invisible or unobtrusive encoding techniques -- techniques which do not interfere with the design of the paper document. One such method has been developed by Anoto [34] 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 recognizing 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 around 50 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. This technology does, however, focus on the capture of handwriting through fairly sophisticated technology – cameras, processors and mobile transmitters. In addition, 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 current implementations, it requires users to consider when pages are complete and 'done'.

The Paper++ approach

In the Paper++ project we explored a different approach to augmenting paper. We commenced with what seemed the simplest way of interlinking paper and digital resources, namely, by pointing to paper documents. Because of our focus on educational domains, and our observations that individuals often use pre-established texts alongside computer systems, we aim, at first, on support for augmented reading rather than writing.

The underlying technical approach taken by Paper++ is quite simple. As with Anoto, we want to use both a paper substrate and a non-obtrusive pattern on the page. However, we focus on the circumstances where users interact with pre-printed documents, where the paper could be a single sheet, a booklet, a pack, or a printed book. These documents could 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. To do this, the pen would need to convert the code into a signal that could be an input to a PC, or another digital device. When a location is selected, supported by a software infrastructure, an appropriate action in the digital domain could 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 would then operate like a touch-screen, only encoding information about location, all other relationships being defined through software by a content provider. This would 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 would be provided in the digital domain.

Obviously this approach relies on some way of establishing a relationship between the paper and the electronic. Similar to Anoto, the Paper++ solution relies on a non-obtrusive pattern, but the process for this is quite different. Rather than using a pattern that can be detected optically, as by Anoto, 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 could 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 from many recent attempts at developing ubiquitous or augmented applications. In particular, it requires 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. This technical choice meant 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.

Refining the approach through simulation studies

One way of short-circuiting some of these technical challenges is to simulate a solution with more readily available technology. Hence, as well as observations of the use of paper in everyday settings, we also undertook a number of ‘simulation studies’. As their name suggests, these aimed at simulating certain aspects of the technology and assessing how users engage with it.

For example, in our first simulation study we used conventional barcode technology to connect a printed encyclopedia to a CD-ROM by the same publisher. We designed a six-page augmented paper booklet, based on the ‘Prehistoric Life’ section of the *Encyclopedia of Nature* by Dorling Kindersley (with permission). Barcode stickers were laminated onto each page and associated with a range of video, audio, graphic and textual information from the corresponding CD-ROM. An example page is shown in Figure 3. Pairs of 9 and 10 year olds used the booklet in conjunction with a Windows laptop, fitted with a barcode reader. They were asked to work together to answer a series of questions on the material, before discussing their experience with us and going on to design their own augmented page. For comparison, half the pairs also performed a similar exercise on ‘Seabirds’, using either the printed textbook or CD-ROM alone. This allowed us to examine the usability and value of augmented paper, and its relationship to conventional and computer-based reading.

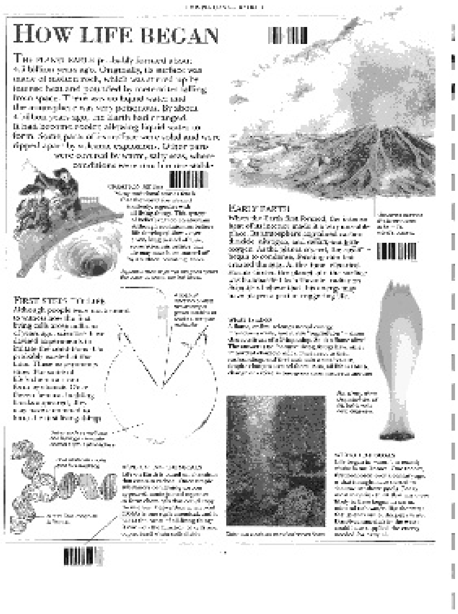


Figure 3. An example page from a barcode-augmented booklet on prehistoric life.

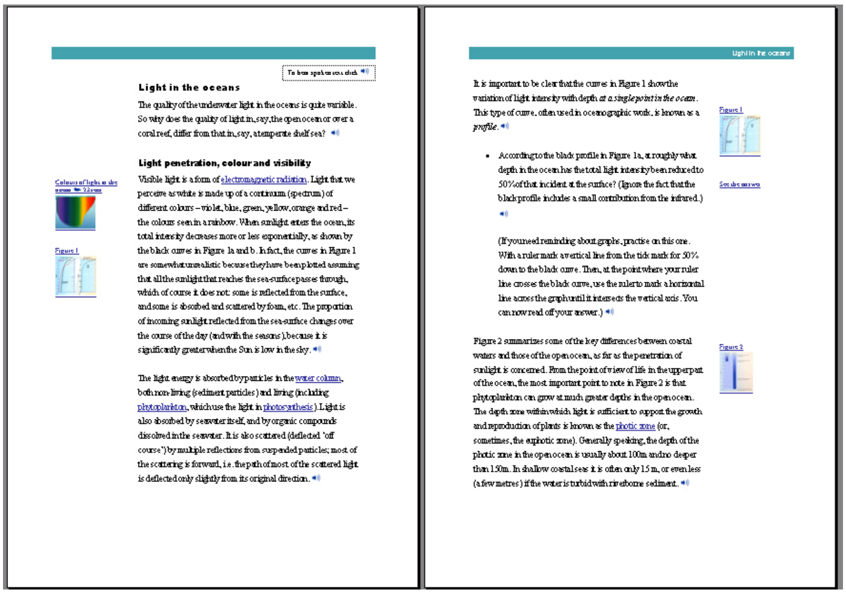
The studies suggested that children could use an augmented paper interface to search effectively for information in paper *and* digital form. Furthermore, user expressed a preference for augmented paper over the use of paper alone. This was despite of a number of difficulties that seemed to hamper information retrieval. For eaxmple, the children were initially confused about what kind of content they were going to encounter from any barcode in the booklet. Without any printed clues, and because of the fun and novelty of revealing hidden information, they tended to swipe barcodes almost randomly at first to see what lay behind them. In the simulation there were no pause, rewind and volume controls for time-based clips. This made discussing or writing down awkward and time-consuming. A final issue, identified by children themselves, was that they could not interact directly with screen-displayed content. The approach of triggering a single instance of screen-displayed content from paper appeared to be too constraining for children who are used to interacting with multiple levels of information through a screen-based interface. It also led to a style of use which involved the constant shifting of attention between the paper and the laptop screen.

We also found that the children enjoyed a range of multimedia enhancements to traditional textbook material. They particularly liked those enhancements which appeared to bring the text to life - such as readings, narration, sound effects and video. However, the means by which the children preferred to access these enhancements, all other things being equal, was through the traditional CD-ROM computer application rather than through the augmented paper booklet. This was partly due to the problems with the augmented booklet mentioned above. However, it also had to do with the design of the associations between the booklet and the CD-ROM in comparison to the internal associations built into the CD-ROM alone. The augmented paper links were effectively 'reversed engineered' from the seeming overlap between content originally designed for paper *or* screen. Conceptually, these links did not always make sense. This meant that they were not as informative as the links built into the CD-ROM and the children noticed this.

These insights had a number of implications for re-designing the augmented paper solution. These affected both its content and the interface. One implication for content was that augmented paper should be considered as a *new medium in its own right,* rather than a vehicle for connecting two existing media. We need to consider the design of original content optimized for reading paper alongside a screen. For the interface the first simulation study suggested incorporating multimedia controls for time-based media on-screen and consistent labeling of active areas of paper with an indication of what lies behind them

Following the initial simulation study we ran a second study, which aimed to explore a richer situation, using more abundant media resources and information content. A collaboration with the Open University gave us access to a set of course materials which deployed documentary video footage from the BBC's ground-breaking 'Blue Planet' series as well as multimedia. This series reviewed life in the oceans over six one-hour episodes. The Open University material referred to these episodes in a first year undergraduate coursebook on Biology.

For the study, we recruited a number of science students, either already at university or else doing science with a view to pursuing a university course. We observed students using the augmented paper booklet with a tablet computer and for comparison we collected data of students using the materials essentially as an OU student would receive them, including paper materials, CD materials and video cassettes (the "analogue materials"). The simulated Paper++ booklet, used a technology which used an optical pattern printed on paper. An example page is shown in Figure 4. Students were given this booklet and when they tapped icons on the paper, the corresponding video clips or interactive diagrams were activated on the tablet computer. Both groups of students were asked to read through the materials and then take a short quiz. After doing the exercise, students in each condition were interviewed about their perceptions of the task and the technology



Light in the oceans

The quality of the underwater light in the oceans is quite variable. So why does the quality of light in, say, the open ocean or over a coral reef, differ from that in, say, a temperate shelf sea?

Light penetration, colour and visibility

Visible light is a form of electromagnetic radiation. Light that we perceive as white is made up of a continuum (spectrum) of different colours – violet, blue, green, yellow, orange and red – the colours seen in a rainbow. When sunlight enters the ocean, its total intensity decreases more or less exponentially, as shown by the black curves in Figure 1a and b. In fact, the curves in Figure 1 are somewhat unrealistic because they have been plotted assuming that all the sunlight that reaches the sea-surface passes through, which of course it does not: some is reflected from the surface, and some is absorbed and scattered by foam, etc. The proportion of incoming sunlight reflected from the sea-surface changes over the course of the day (and with the seasons), because it is significantly greater when the Sun is low in the sky.

The light energy is absorbed by particles in the water column, both non-living (sediment particles) and living (including phytoplankton, which use the light in photosynthesis). Light is also absorbed by seawater itself, and by organic compounds dissolved in the seawater. It is also scattered (deflected 'off course') by multiple reflections from suspended particles; most of the scattering is forward, i.e. the path of most of the scattered light is deflected only slightly from its original direction.

Figure 1

Light in the oceans

It is important to be clear that the curves in Figure 1 show the variation of light intensity with depth *at a single point in the ocean*. This type of curve, often used in oceanographic work, is known as a *profile*.

- According to the black profile in Figure 1a, at roughly what depth in the ocean has the total light intensity been reduced to 50% of that incident at the surface? (Ignore the fact that the black profile includes a small contribution from the infrared.)

(If you need reminding about graphs, practise on this one. With a ruler mark a vertical line from the tick mark for 50% down to the black curve. Then, at the point where your ruler line crosses the black curve, use the ruler to mark a horizontal line across the graph until it intersects the vertical axis. You can now read off your answer.)

Figure 2 summarizes some of the key differences between coastal waters and those of the open ocean, as far as the penetration of sunlight is concerned. From the point of view of life in the upper part of the ocean, the most important point to note in Figure 2 is that phytoplankton can grow at much greater depths in the open ocean. The depth zone within which light is sufficient to support the growth and reproduction of plants is known as the photic zone (or, sometimes, the euphotic zone). Generally speaking, the depth of the photic zone in the open ocean is usually about 100m and no deeper than 150m. In shallow coastal seas it is often only 15 m, or even less (a few metres) if the water is turbid with riverborne sediment.

Figure 1

Figure 2

Figure 4. An example page from an augmented booklet on biology

From the studies and interviews the experience with the Paper++ simulation seemed to be more *consistent*, *assured*, and *suited different types* of student. Some students expressed a preference for book-learning, some for screen-learning. The students using conventional video and computer would tend to find themselves protractedly watching the video and superficially skimming the booklet, or vice-versa; whilst with Paper++ the different types of learner seemed to behave similarly. It also seemed that those students using the conventional media were also more inclined to look for guidance, feedback and reassurance that they were doing the exercise correctly.

The experience with the simulated Paper++ technology appears comparable to *browsing* through a book. Contrary to expectations, it was not quite like "surfing" a purely digital domain. As an illustration, with the conventional materials, several students browsed back and forth in the booklet, looking back at a diagram, interleaving a thumb in the text. With the simulated Paper++ technology the diagram was in interactive form, and clicking and looking at the screen was equivalent to turning a page. Students, therefore, could proceed through the booklet from beginning to end, exploring back and forth to the digital screen, but never needing to turn back a page.

The simulation studies produced materials illustrating the challenges and work in designing for an augmented paper approach. These remained simulations, successfully incorporating many of the functions we wanted, but demonstrating some of the technological and content design requirements of a Paper++ solution.

4. AN AUGMENTED PAPER TECHNOLOGY

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 innovations would then be the use of conductive inks, the design of a pattern that could encode locations and a reader to detect these locations from the surface of the paper.

The project relied on drawing upon developments in conductive inks which have emerged from innovations in conductive polymers in the 1970s. At the commencement of the project there were a number of innovations in these and related technologies in order to print electronics, to produce plastic conductors and related developments. It appeared that invisible conductive inks were available, at least in trial quantities However, although having good conductive properties, the inks available were not robust and failed abrasion tests. They required another coating (or substrate) and thus transformed the flexibility of the material or reduced the visibility of any printed artwork (i.e. they appeared black or an opaque blue).

During a workshop organised by the Disappearing Computer Project it emerged that research undertaken by one of the partners in the ACCORD Project (Acreo AB of Sweden) was of direct relevance to the solutions being explored by Paper++. Acreo who had been working on derivatives of a conductive polymer called Pedot (Poly(3 4)-ethylenedioxythiophene). This workshop gave rise to a separate 12 month DC funded project called Superinks, the primary goal being to produce a the printed conductive solution that met the Paper++ requirements. This mini project was successful printing a pale blue/grey Pedot pattern of reasonable conductivity over the artwork. This was visible but not obtrusive.

We needed to encode several A4 pages to a resolution of a few millimetres. The current solution encodes 8 A4 pages, each divided into 16 columns and 32 rows. In each cell we print a code comprising a start sequence, 3 bit address for the page, 4 bit address for the column and 5 bit address for the row. The resulting pattern resembles a complete tiling of very pale bar codes 8 mm high and 13 mm wide. Each bar code represents a unique address of page, row and column. A simple software method to interpolate horizontal position to 1/10 of a code cell gave the final resolution of position to 1.3mm by 8mm.

With regard to the detector we needed a completely ambidextrous solution for all users which prevented abrasion of the conductive ink. The current solution is a symmetric tip resembling a retractable ball point pen. The outer casing has a large radius of curvature outer electrode that only applied a low force per unit area on the artwork. The second electrode has a small radius central spring-loaded contact that applies a constant low force on the artwork. The resistance between these two electrodes depends on the conductivity of the surface and these change as the user "swipes" across the surface. In our current solution the change in resistance is converted into a frequency modulated signal that can be readily decoded by interfacing through a PC sound card. Thus the solution comprises a coaxial swipe reader that is stroked across small conductive, Pedot, bar codes printed over artwork (see Figure 5).

Fig. 5. 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.

The software solution

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 provided only a one-to-one correspondence between locations on a page and electronic resources. We realized there were applications where it might 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 was printed on the page it did not have to be tied to fixed actions or indeed simple shapes. As well as allowing for flexibility in the objects that were 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 [26]. This allowed specific media types to be integrated through a plug-in mechanism as indicated in Figure 6 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.

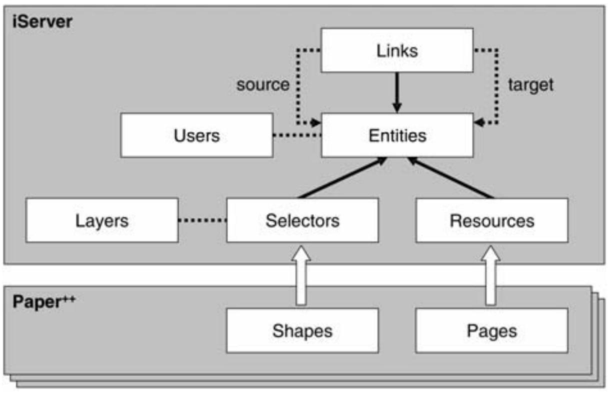


Fig. 6. Generic Cross-Media Link Server

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).

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 [32]. 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). 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 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 7 shows a screen shot of the authoring tool.

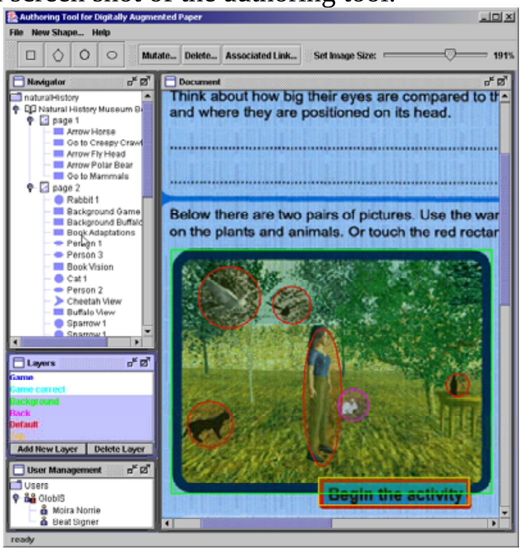


Fig. 7. The authoring tool using material developed by the project. It is also possible to see the positions of the coding scheme in the figure (right hand window)

5. AN INTEGRATED DEMONSTRATOR

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. The primary aim of the worksheet was to tie together the gallery experience with focused activities that take place in the Investigate Area – a work space for children to handle and explore real museum exhibits and access digital media.

In collaboration with museum educators and designers, we developed a worksheet on ocular adaptation of animals. Children could use the worksheet alongside the exhibits and then when in the Investigate area they could examine the digital content, and explore further information in a selection of reference books, to complete the tasks on the worksheet. \

The worksheet was 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 was printed on a thick (card-like) paper (250 g/m^2) for ease of use around the museum (see Figure 8). The participants used the co-axial pen developed in the project to trigger digital media from 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.

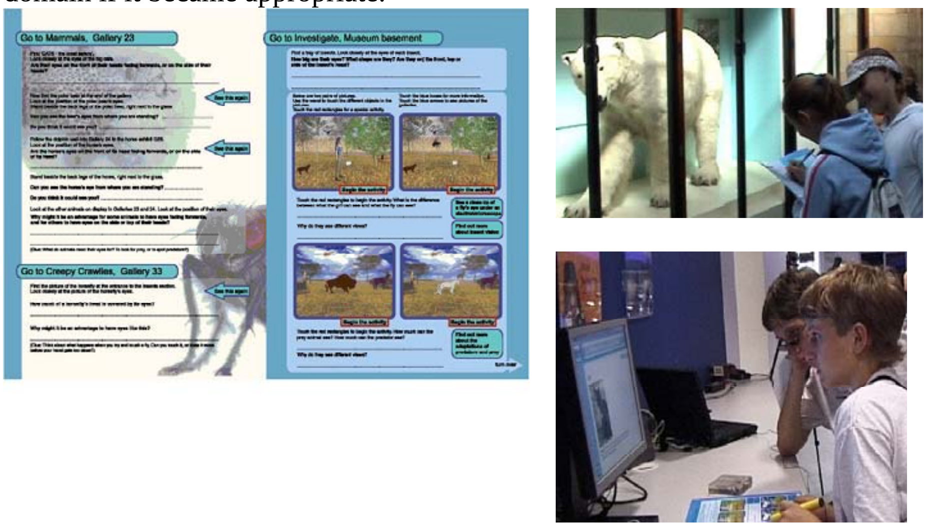


Fig 8 The central 'active' pages of the worksheet (left). Layers are invoked by activating the pictures on the right hand side. The augmented paper worksheet in use with the mammals gallery (top right)m and in the Investigate Area (bottom right)

Active areas on the worksheet are indicated by darker blue boxes (see Figure 8). On the left page the worksheet contains several links to digital images of relevant gallery exhibits so that children could view these again without having to revisit the gallery itself. On the right side of the worksheet there are a series of images which can be used in two different modes. In the default mode touching on the animals in the images shows video footage of them in their natural environment involved in activities which demonstrate reasons for their particular ocular adaptations. Touching on the 'Begin the activity' area triggers a game mode. This game enables them to test their understanding of the concepts of ocular adaptation explored so far. The game is comprised of audio instructions and feedback, but is played out on the paper. This interactive element required the use of complex shapes defined by the designer, and a basic use of multiple layers.

Once the paper worksheet and digital content were designed and produced we used the authoring tool to assemble the digital content and create the links with the paper sheet.

The principal achievement of the trial was the production and demonstration of a complete chain of the technology involving participation from seven 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 was 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. 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.

However, despite the concept being clear the technology was still at too preliminary a stage to be assessed in any detail with respect to its use. Even though laboratory experiments showed a 'hit-rate' for selecting an active paper region 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 trial 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. The demonstration provided evidence that such an approach was feasible and that elements of the technical chain could be integrated.

6. DISCUSSION

Paper ++ reflects the growing commitment in system development to augment everyday artefacts with associated computational resources. It has been an attempt to preserve the integrity of paper whilst enabling complex and systematic links to digital materials. While there are other existing solutions, these have largely focused on enhancing writing or have radically transformed the material qualities and characteristics of paper.

Although, the project focused on exploring applications in educational domains, Paper++ technology could be applied to numerous other settings associated with either work or domestic settings. For example, one could envisage applications for medical environments where standard documents or bespoke materials produced by professionals, practitioners or even patients are associated with electronic resources. As another example, 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.

In developing an augmented paper solution, however, we have found many complex issues that need to be considered and worked through, ranging from technical issues right through to the practicalities of designing content and supporting the larger scale production of hybrid paper and digital documents. Many of the technical and design issues we have already discussed, however there are other lessons that we have learned throughout the 3 year process.

For example, Paper++ technology requires that we 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.

Another set of lessons had to do with the design of content for hybrid paper-digital documents. Our initial conception of how the paper and digital could be interrelated was by simple linking – an action on a page would invoke 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 in the Natural History Museum. 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 ten 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, which represented another strand of work within the project [22]. 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. At the very least, it requires editing clips so that they are coherent and consistent with the associated paper content. 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, a number of different versions of digital materials for the same paper document if that material is to be varied depending on the user or the context. There is therefore a great deal of additional authoring work and new sets of skills to support the development of augmented paper documents. 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. This has longer term implications for the kinds of organizational processes needed to support the creation of augmented paper within publishing.

This also has implications for the kinds of authoring tools that need to be provided for the creation of Paper++ documents both for content providers and for end users. 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 developments of this kind, 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.’

All of this shows that although the concept of augmenting reading seems simple and straightforward, developing a pervasive and resilient artefact may not be enough. Drawing together the many elements of the

Paper++ project has shown that 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. All of this only serves to highlight the fact that our studies have only begun to touch the surface. Yet, despite the complex sets of issues that emerged throughout the course of the project, this kind of attempt to bridge the paper-digital divide should, we believe, be at the heart of an agenda to consider how the disappearing computer integrates with the real world.

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