Brunel University
School of Engineering and Design

Julian Wood

Design and application of a contact barcode reader, for use on low-visibility printed conductive patterns

MPhil Thesis

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Supervisors: Prof. D. Harrison, Dr D. Southee

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Abstract

This thesis presents the design and development of a hand-held electronic reader, designed to decode conductive patterns printed on a paper substrate. Data read from the patterns, by the reader, is used to trigger events in the digital domain. The reader and associated conductive patterns are devices for linking paper documents with the digital world.

The patterns are formed by masking conductive-coated paper with a non-conductive, printed lacquer. The reader is a low cost and ergonomic device, capable of transmitting the embedded data from the conductive paper to the computer. The first reader designed and developed was tethered to a computer by data cable, using the USB communication protocol. The second design was developed further, with transmission of data achieved by replacing the cable with short-range Bluetooth wireless technology. Both devices were designed and developed using embedded systems and low cost electronic components.

Additional work was undertaken to optimise the device's mechanical structure, ergonomics and integration of hardware. Alongside the development of the reader, test and development work was carried out to optimise the printed media, in materials and design.

User trials demonstrated that the complete printed and reading system was functional, with varied rates of success among participants. Further work is required to improve the conductivity of the coated paper, and the accuracy of the decoding algorithm.

Acknowledgements

Our gratitude goes to the EU FP6 for funding the research project and to all of our partners: King's College London, Acreo AB, Anoto AB, ArjoWiggins SAS, ETH Zurich, Malmö University, Pearson Education and Edexcel, and all the participants of the user studies who volunteered their time.

Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

Paper continues to be a pervasive resource throughout society. Reasons for this are reported, and include paper's mobility, low cost, portability and its facilitation of mutual access and collaboration (Luff, Heath 1998) [16]. In contrast, digital displays are more expensive and heavier, making them less portable than the paper they aim to replace, [8]. The concept of invisible, or at least non-obtrusive, patterns as information carriers for printed documents has also been reported (Kise et al. 2000) [13]. A review of previous work in developing relationships between digital content and paper can be found in 'The Disappearing Computer' (Luff, et al.2007) [14].

The research work reported in this thesis aimed to integrate the use of paper and digital applications, in the form of augmented paper. The paper is termed 'augmented' in that it contains embedded digital information. One approach to this integration was through the development of a conductive-pattern contact reader. The reader was intended to be a very low-cost item. The conductive pattern was intended to be mass-produced as part of a printed, published document, without specialist production requirements.

1.1 Objectives of the research

- To review the current state of the art, with respect to digital interface and interaction devices for linking paper and paper-based tasks with the digital domain.
- To determine appropriate materials and methods for the design and fabrication of a low-cost, tethered prototype system, able to interface paper documents with the digital domain.
- To design a wireless system able to achieve the same.
- To characterise and evaluate the system, with respect to the developed hardware and printed media, by way of testing and user trials.

- To identify areas of interest requiring additional work.

1.2 Background

The contribution to the development of a contact barcode reader was part of a European Union (EU) project “PaperWorks”, itself a continuation of an earlier project called “Paper++” [22, ,15]. Paper++ was an attempt to develop a system which would integrate digital information with printed paper media. In the Paper++ environment, the barcodes were meant to be ‘invisibly’ printed over artwork, so that the medium would appear to be a normal printed paper article. The printed patterns were visible, however, due to an unavoidable colour cast in the conducting ink material. The contact reader recorded the changing pattern conductivity by being drawn across the printed patter. The encoded information, such as the page number, row and column, was decoded to determine the position of the reader. This related to the position on a page of a document in digital form (Luff, et al. 2003) [29, p.7].

The work in this thesis aimed to improve the reliability of the hardware, which had previously been poor. It also aimed to be able to read a truly invisible conductive pattern, created by masking sections of conductive paper with an insulating lacquer.

In the preceding Paper++ project, a barcode reading device was developed, similar in scale to a writing pen. The barcode reader was constructed with surface-mount components, making the printed circuit board (PCB) very compact. The PCB was housed in a tube, part of which was aluminium, which formed part of the sensing circuit (Figure 1).

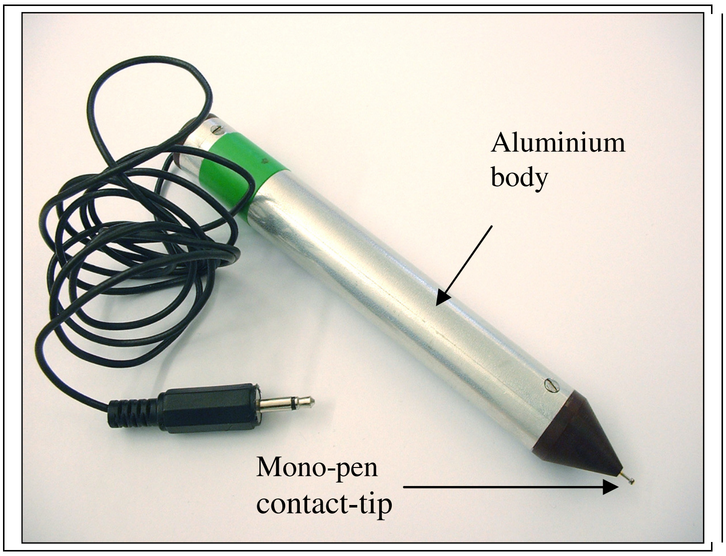


Figure 1. Paper++ barcode reader

The circuit was compact due to the limited signal processing done in-pen, and consisted of battery, amplifier, and voltage to frequency converter, with associated passive components. The barcode reader used the microphone input of a computer sound card for signal input. This system relied on the "mono-pen" transmitting a string of pulses to the computer, via the sound card. The "mono-pen" was so named as it used a single electrical contact point at the tip. The user, by touching the paper, formed the conductive path back to the pen body. These signals were then translated from the printed code pattern, producing a positive or negative response from the PC interface application.

The working principle is depicted in Figure 2. The (blue) dotted line represents the conductive path through the body, from the hand contacting the paper, to the hand holding the reader. The two hands may be considered part of the conductive tip of the reader. The (green) unbroken solid line represents the audio signal cable connection from the tethered reader to the sound card of the computer.

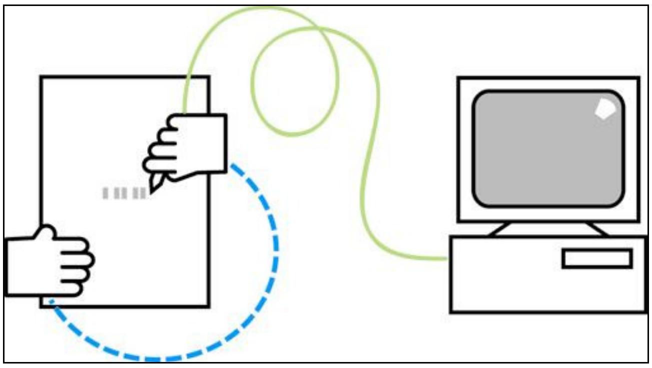


Figure 2. Principle of operation of 'mono-pen' single contact point tethered reader.

The intention was that, while working through the text or other artwork, the user could swipe a relevant area of the paper and link to more information on a computer.

1.3 Overview of the design of the new Brunel tethered barcode reader

A schematic showing the different stages of the working principle of the complete Brunel barcode reading system is shown in Figure 3. The (green) dashed line highlights the processes taking place within the device, which is fundamentally different to the preceding project model.

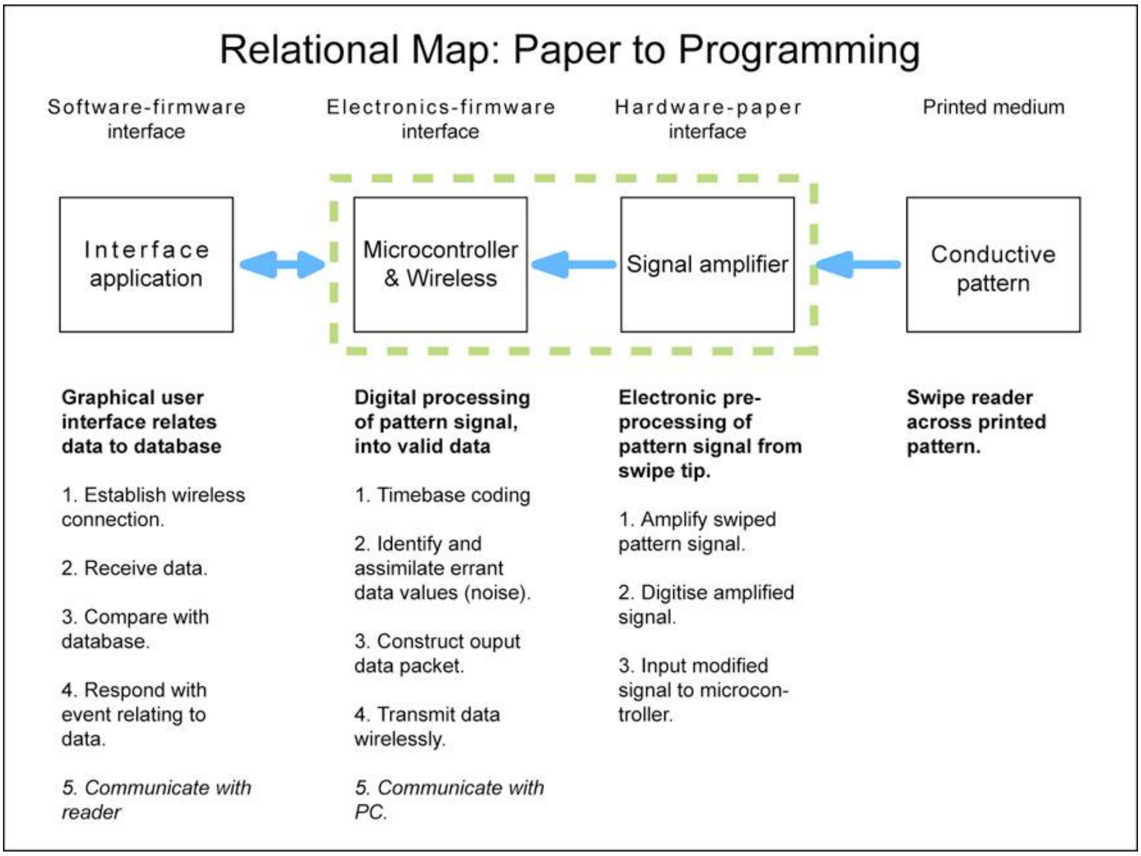


Figure 3. Schematic model of the system, using wireless reader transmission as example.

The Brunel reader developed by the author, senses the conductive patterns by means of electrical contact. The generated signals are decoded, and the information is transmitted to the software application via a USB cable, or wireless module. The contact barcode reader is a hybrid device made up of four discrete modules:

- The conductive tip that scans the patterns on the paper.
- The electronic hardware comprising of signal amplifier and filter, and its associated components, for preliminary signal conditioning.
- The microcontroller and firmware responsible for processing the conditioned signal, and interpreting the pattern waveform. The microcontroller decodes the waveform data, and outputs a value to be transmitted via a connection to the computer.
- The software interface on the host computer that assesses the input values, and creates ‘events’ in the digital world.

1.4 Thesis Structure

Chapter 2 reviews the literature on reader devices for augmented paper. Chapter 3 describes the design and development of the reader conductive tip, casing and interface design. Chapter 4 discusses amplification, signal conditioning, and power management. The firmware and software development is described in Chapter 5. Chapter 6 describes the development of a digital pencil interface device. Chapter 7 describes evaluation of the system through user trials. Conclusions are drawn in Chapter 8.

Chapter 2: Literature review

This review describes the current state of the art, with respect to digital interface and interaction devices for linking paper and paper-based tasks with the digital domain. It identifies the gap in knowledge which the thesis goes on to explore.

2.1 The persistence of paper

Currently, the use of paper, in the office environment as example, is prevalent and seemingly unstoppable. It is just so useful, as pointed out by Sellen and Harper in *The Myth of the Paperless Office* [26], given that many people may collaborate on the same documents. Having other printed documents alongside that are being read at the time, allows for organisation of the material in a visually understandable manner.

A laboratory study conducted by Sellen and Harper, to investigate the differences between reading a printed document and the same on a screen, arrived at four main conclusions. The first was that navigation of a document was linear on-screen, whereas it was unrestricted by the ability to flick through the pages of a physical document. The ability to rearrange the document's layout was also considered important, while the lack of this easy ability caused frustration with the electronic copy. The paper copy could be annotated, while the electronic copy had no facility for doing so. Lastly, the process of alternatively reading and writing was possible with the paper document, while it was not with the electronic copy.

Of course, the use of and access to electronic media is important, and very powerful. Indeed, in generating copy, the use of electronic aids is invaluable, as the constant rearrangement of, change to, deletion and addition of passages to this text would not have been as easily facilitated using a typewriter.

The goal of augmented paper is to combine the benefits of paper: physical interaction, navigation, layout manipulation, and annotation, with the flexibility of electronic media.

2.1.1 Linking devices and hardware solutions: wands, barcode readers, pens, tablets, and cameras

The first device built to convert data into paper-based information was the 'stock ticker', invented by Mr. E.A. Calahan of the American Telegraph Company in 1867, using Morse code symbols punched into a paper tape [10]. The ticker, so known for the sound of its action, relayed stock prices through telegraph links, and output them in near real time, to remote printers. Thomas Edison later patented his own version in 1867, which output the stock values in alphanumeric characters, making them more easily understandable. The machines only worked as output devices.

Punch cards for programming computers were developed as early as the 19th century, by Charles Babbage, for use with his mechanical calculator. True punch cards, as a mature computing system, were in place in industry by the 1940's [11]; IBM introduced its 5081 series programming card, which became ubiquitous in the industry. Annotating these cards became possible with the 'mark sense' card, developed by IBM; using an 'electro-graphic' pencil, a card with basic punched information could be updated with stock changes by marking defined areas on the card. A reader would sense the pencil marks, and punch holes as directed, for later use in a card reader.

2.1.2 Barcode history and symbology

Bar codes encode information along one dimension, with intervals of alternating diffuse reflectivity, usually black and white in colour. It must be emphasised that although this PaperWorks research project focused on conductive patterns, rather than optical, the discussion of barcode symbologies is relevant due to the adoption of the encoding scheme.

A barcode consists of bars (optically coloured) and spaces (optically 'clear' background). There are two methods of encoding data using bars and spaces: delta and width. Delta codes have a minimum 'interval', which corresponds to a '1' or '0'. Thus, the width of the bars and spaces are directly related to the encoded data: '1110' would be represented by a bar three times as wide as the space following it, etc. Width encoding represents a '1' as a wide bar, and '0' as a narrow space. The proportions between the two may vary, but there are only two widths to contend with.

The basic requirement for printed barcodes was that they be scalable, readable at variable distance, and at variable speed (to accommodate hand-scanning). This imposed the constraint that such printed codes be self-clocking, meaning that both the number of modules, and the number of bars and spaces per code word be fixed. This assists with error trapping. Delta codes are required to have a fixed number of bars and spaces; width codes have the same requirement, as well as a fixed number of wide elements to achieve a fixed overall width. It has been reported that to overcome the lack of synchronous scanning (Pavlidis, et al., [23]), the only way around the lack of a clock is to allow only contact scanning, and require that all codes are of the same scale.

The first barcode solution had a patent application filed by Bernard Silver and Joseph Woodland, on 20 October, 1949. The solution was as a result of an incidental request by a president of a chain of food stores, who wanted to record details of products, at the point of sale [1]. The first commercial use of barcodes was at a retailer, June 26, 1974. That day, a checkout clerk passed a pack of Juicy Fruit gum over a bar-code scanner at a Marsh supermarket in Troy, Ohio. The barcode format was the Universal Product Code (UPC), a development of an IBM format [19].

Today, there is a great variety of barcode symbologies in use. Most products today use a version of the UPC code, which is the European Article Number (EAN) code. This can be EAN-13 or EAN-8. The UPC code is an example of a delta code, while Interleaved 2 of 5 code is an example of a width code. These are fixed-length barcodes, and are normally scanned by reflected laser beam. A development of the 1D barcode, driven by the requirement for greater information density, was the introduction of stacked barcodes, which were the precursors of 2D codes.

Over the past few years, it has become more common for these '1D' codes to be read by camera optical imaging systems. 1D barcodes have, in some areas of industry, become superseded by '2D' codes. No longer comprised of bars, but rather pixels arranged in a square area, 2D barcodes can contain more information, and sustain greater image degradation. 2D barcodes are decoded by camera imaging systems, much like that of the Anoto pen.

A possible conductive solution to the optical 2D barcode was proposed in the SuperInks project [29, p.40], where two barcode patterns would be overlaid on the paper, one at right angles to the other. The requirement was for variable conductivity ink printing, so that barcode ‘A’ would be of conductivity values 0 and 1, and barcode ‘B’ would be of conductivity values 2 and 3. The x-y positional data would be separated by the two barcode axes; an angled swipe would cover the x and y axes of the printed document. The idea was that the combinations of ink conductivities would generate a signal which could be interpreted and separated into the two axes, and thus provide absolute location data.

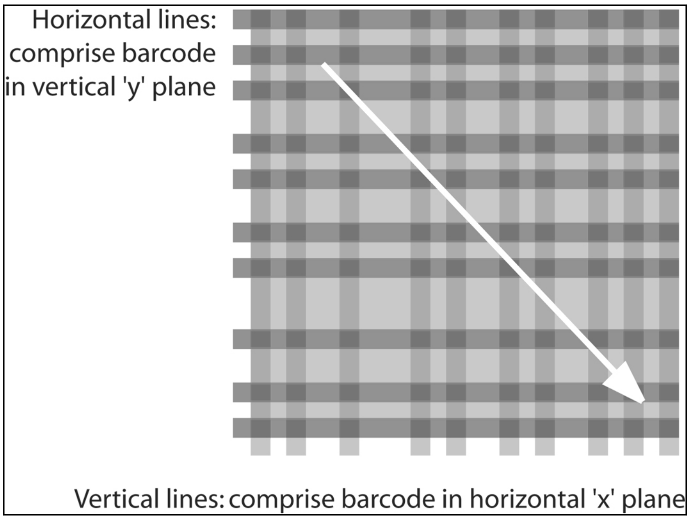


Figure 4. 2 Proposed "D conductive barcode proposed as future investigation.. White arrow indicates swipe direction across both barcodes.

While the PaperWorks project requirements did not specifically state the demand for the conductive equivalent of an optical 1D barcode solution, the fact of the included conductive ink patterning did make such a solution obvious. The system was required to be simple and cheap, which ruled out complex pixel-decoding technologies. The printing issues, with regard to resolution, ruled out complex barcode symbologies, such as EAN-13 and its multiple-width format.

2.1.3 Integrated systems utilising barcodes and other patterns

Conventional barcode technology, such as optical reflected pattern systems, has been in commercial use since the 1970's. The patterns have been used as item identifiers for stock control in commercial and industrial applications. Every item to be found in a supermarket will have a barcode printed or affixed to it, so that the barcode, by its ubiquity, has become almost invisible. Our interaction with barcodes is largely incidental, as our experience is confined to watching items being passed under a scanner at the supermarket till. Royal Mail and other mail companies use barcodes to track the progress of their items through the transport system.

Later consumer-oriented applications have found uses in updating software in cameras such as the Canon EOS 10s (Canon Corporation 1990), programming remote control units for video recorders, children's' toys such as Barcode Battler" (Epoch 1991) and web linking (":CueCat").

- ":CueCat", a short-lived contact optical scanner and software, given away freely. Introduced in 2000, the device promised to link printed articles to related web pages; scanning a barcode with the tethered optical contact scanner brought up a link within the article's or advertiser's website. The company behind the technological give-away was 'Digital Convergence', and their web statement was:

"*The :CueCat (Keystroke Automation Technology) optical reader is a free hand-held device that is attached to the computer. About the size of a mouse, the :CueCat reader will change how you use the Internet forever by interacting with*

Digital:Convergence's proprietary codes, ISBN codes, UPC codes and many others. With just one swipe, the :CueCat reader instantly transports you to a specific Web page. It's that easy! " [7]

The scanner was not a success. Primarily, the issue was that the users could just as easily visit the site conventionally, and found the :CueCat device redundant.

Figure 4. Movie still, showing the :CueCat in use.

Canon's barcode system designed to program specific exposure functions in their single lens reflex cameras. Utilised in EOS 10/10s and 100/Elan cameras (1990 – 1996) [9]. The barcode reader was a contact optical device, which used Interleaved 2 of 5 barcodes to program preset exposure modes in the camera. The barcodes were supplied with a booklet, which was aimed at beginners, as the set of preset exposure modes were designed to deal with common but complex situations such as macro photography and night-time shots. The booklet and reader were novel, and suited to their application. However, they were designed for occasional use, and not intended for advanced users.

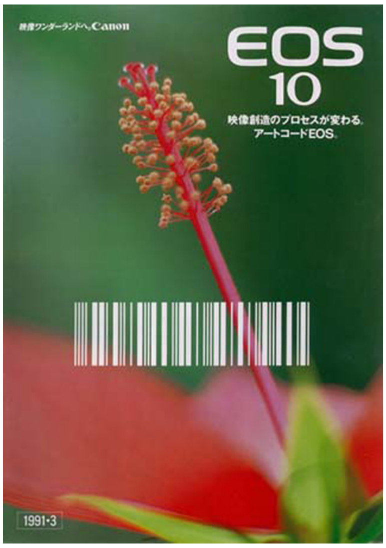


Figure 5. Barcode booklet for preset exposure modes, available with Canon barcode reader.

Figure 6. Epoch (1991) 'Barcode Battler' hand-held game console and packaging [16].

In 1990, Epoch Co. Ltd released a hand-held game console in Japan, and later worldwide (1991) [5], which used barcodes as data input [4]. The idea was that, like the later Pokemon game series, users would fight battles between characters defined by barcodes. The game was originally supplied with barcode cards which were swiped, but later devices could read barcodes printed on domestic goods. Thus, the game allowed the user to explore the myriad and unknown potential of a superstore's worth of 'characters'. This was an interesting application of barcode technology, given that the barcode is usually placed in the background of a product's packaging. This game made the barcode the focus of the product packaging.

2.1.4 Anoto pen and related technologies

Currently, the only known commercialised high resolution handwriting generation and recognition product is the Anoto-based digital pen and paper system. This was the only 'digital pen' which could interact with printed paper, as opposed to the many systems which required a stylus and pad. Other 'digital pen' systems used sonar technology [24] to record the location of the pen on the pad. Thus, these other devices are not direct competitors to the Anoto pen, as they rely on a hardware support system to interface to a computer. Microsoft later proposed their own, similar system to that of Anoto.

The Anoto pen is a conventional looking pen, albeit much thicker than a BIC Crystal, and can write on paper with a ballpoint tip. The unique feature of the Anoto is that it reads a fine printed pattern on the paper [8], using a small infra-red camera mounted offcentre to the pen tip. The pen makes the calculations necessary to determine its position on the paper, in real time, and records a writing or annotation sequence for later upload to a computer. The software interface allows the handwritten notes to be displayed as a bitmap image, or can be translated into editable text.

The pattern used by the Anoto pen is comprised of dots, arrayed about a 0.3mm spaced grid. The dots are offset from the intersection of gridlines, and it is the uniqueness of each 6x6 group of offset dots which provides the x-y positional data for the pen to decode. As the pen moves across the paper, the camera captures images of arrays of dots, up to 100 times per second; each group of dots is different from the next by the overlap of one grid line. Thus, the resolution is determined by the grid spacing, as the second group of dots will comprise most of the first, but including a new line of dots in the direction of travel, and discarding the last line of dots from the previous group.

The dots comprising the Anoto pattern are printed on normal paper. This alters the appearance of the paper slightly, in that it appears to be a light grey tone. It is not obtrusive, however, and all the affordances of paper are retained. The complexity of the Anoto system does not offer, as yet, fully interactive applications. Several companies have produced the basic Anoto pen under licence, including Maxell, Logitech, Nokia and Leapfrog.

The pens available save the information within the pen, and the information can be uploaded to the computer as a batch, or after each page. Several A4 pages worth of handwriting or sketches can be saved. The main purpose of the pen was to convert handwriting into text, but applications have been created [27; Chapter 7, p.175] which could greatly increase the performance and interactivity of the pen. The use of the Anoto pen is naturalistic, and requires little training. There are some differences, in that the user must tick a part of the paper to upload the recorded page data to the computer. Each 'page' of work is therefore completed when the user decides it.

There have been several attempts to build stand-alone digital pens, an example of which is the Memo-Pen (Nabeshima, et al. 1995) [20]. This was interesting, as it relied on relative positional coordinates, calculated from the start point of writing. As such, it required no special paper or interface hardware. The pen used a camera to record the position of the pen nib, and a stress sensor to calculate its movement, relative to the line drawn. Straight lines proved problematic, as throughout the duration of the stroke, nothing changed to suggest that the pen was actually moving, as opposed to being stationary. This is where the absolute positional pattern of the Anoto pen proved better.

A similarly-equipped pen, using a switch and video camera, was the PaperLink concept (Arai, et al. 1997) [2]. Unlike the Memo-Pen, the PaperLink pen extracted content from printed or written documents, and linked it to digital content. It was also configurable to a limited extent, in that it could assign functionality to scanned content, by labelling it as a command, or as data. User-defined commands could be applied to the content being recorded. PaperLink did not record text or images through the action of creating them.

Remote pen capture systems have been trialled, such as DigitalDesk at Xerox EuroPARC, which used video-capture systems. The system works with a camera above a desk, which tracks the position of the pen and paper (Wellner, 1991) [30]. More local technologies have become available, which use ultrasonic triangulation to track the motion of pen on pad, such as Seiko's 'Ink Link', and 'Mimio' for flip-chart use.

These systems all require hardware which is external to the pen (or wand, or stylus), and really interact with the surface on which the paper is placed, rather than linking the position of the pen to the paper independently. As such, these systems are less portable that a simple pen and paper setup.

The use of visible marks on paper has been researched, as barcodes are a known technology. The maturity of the technology has allowed simple applications to be built, linking paper and other physical objects to electronic resources Mima 1991[28]. Barcode technology, already proven, is used in a range of applications, such as logistics, healthcare and publishing. Thus, it is potentially useful in being able to integrate documents into these applications, using tagged positions on the document.

More highly-developed systems encode the linking information in the paper space. Examples of this are the visible patterns of Xerox glyphs, and CyberCodes, printed on a page, and detected by camera . [21]. RFID (radio frequency identification) tags can be detected by (near) contact. All of these approaches are visible, and so the augmented aspect of the printed document is clearly visible. The aim, of course, is to submerge the augmented content, such that it is non-obtrusive, or invisible.

2.1.5 Paper++ and SuperInks

Two EU-funded projects were launched to investigate the options of using paper as an input device, SuperInks [29] and Paper++ (Luff, et al.; Chapter 2, p.6) [15]. The SuperInks project of 2002-2003 was the first to trial the concept of using printed conductive patterns as location tags on paper, and its key aim was to develop a suitable ink and printing technology for the Paper++ project. Conductive inks and coatings have been used for their static dissipative properties on bags for electronic components, and on clear films. The proposed outcome of the project was to develop an ink and system that would utilise the conductive patterns in a similar manner to that of Anoto.

One major aim of the projects was to produce an augmented paper document which could be read by a simple, cheap device. The conductive pattern would be printed over the document, encoding the positional x-y locations. The code would be interpreted by the contact reader, and interfaced to a PC; the PC would play a sound, link to a web page on a browser, or activate some other digital function.

The first detector configuration consisted of a 'comb', with sufficient fine inline electrodes to enable a location barcode to be read by single contact. The comb spanned the length of the pattern, and adjacent comb 'teeth' signalled contact with conductive or non-conductive areas within the pattern. Thus, the pattern could be read with a simple pointing action. However, the comb reader was bulky and it proved difficult to assure full contact of all electrodes.

The next Paper++ detector used in the project used two electrodes to make contact with the paper. The detector was styled as a large pen, with basic circuitry contained within. The action of reading the pattern was a single swipe across it. The printed pattern code was converted into a frequency modulated signal within the pen, which allowed differentiation between conductive and non-conductive areas of the pattern. The pen was tethered, so required close proximity to the PC it interfaced with. The output was transmitted to a PC via a microphone jack, connected to the PC sound card. Bespoke software decoded the pulse signals, and signalled a response to the user.

Available conductive printable inks were not invisible. Silver conductive inks were successful, but highly visible. Attempts to print the available organic inks on paper resulted in obviously visible patterns. Heat curing of the organic inks caused them to darken, and lose conductivity.

2.1.6 Similar contact technologies

One of the Paper++ conductive pattern detectors, “Mono-pen”, utilised the property of the human body to conduct electrical signals. This property was a core component of a prototype research study into human-computer interaction, in the form of the Body Coupled FingerRing (Fukumoto, Tonomura 1997) [18]. The concept was to replace the small keyboard of a PDA with rings, worn on the user's fingers, making it a 'wearable' PDA. A touch-typing code was devised to translate the taps from each finger into usable input to the PDA. The connections from the rings to the transmitter/receiver for the PDA were by skin conduction, and the transceiver communicated wirelessly with the remote PDA.

Another study into human skin conductivity, and its use as indication of physiological arousal, was performed using the 'Galvactivator' (Picard, Scheirer 2001) [25]. The device was built as a glove, to be worn by a user; the glove indicated skin condition by outputting calculated values to an LED display. Proposed uses for the application were communication facilitation, and possible aid in the learning process of autistic children.

2.1.7 Natural History Museum trial of augmented paper

This was undertaken in June 2003. The trial demonstrated the concept of augmented paper, and the interaction of the complete technology chain. The hardware comprised a specially designed and printed double-A4 folded glossy brochure, tethered pattern reader, and associated software. The context of the demonstration was educational, but the activity was a trial of computer supported cooperative work, supported by the augmented paper technology (Signer 2005) [3].

The computer-paper associations between digital content, and that printed on the paper, were made using the i-Server software application, and trialled at the Edinburgh Fringe Festival; developed by ETH Zurich (Luff, et al. 2004) [17]. While the augmented paper patterns resembled 'normal' barcodes, the functionality of the barcodes was not limited to direct linking of encoded data on the paper; i.e. the barcodes were not considered as buttons. Rather, the surface of the paper was tiled with the barcode patterns, so that it could be considered completely active. This avoided the issue of users being influenced by the placement of barcodes on specific sites on the paper. The Paper++ approach used indirect encoding of locations; the associated information, link and output (on the PC) were software-defined, and offered the possibility of flexible outcomes for the same area being scanned.

The brochure was used as part of a mixed-media lesson, where parts of the brochure would be filled by hand, and other parts scanned with the reader to generate digital output. Some components of the user experience were computer-based, where a conventional mouse and keyboard were used to navigate deeper into the digital domain.

An interesting aspect of the project was that, although the printed digital patterns were visible, the fact that they covered the full print area of the document did not cause observable distraction. It was as if the pattern was part of the background artwork, and thus became 'invisible' to the users, due to its uniformity.

2.2 Summary

This chapter has explored the literature related to reader devices for augmented paper. An understanding has been developed of the key issues in this area. The literature has confirmed confirmed that low cost reader devices to read invisible conductive patterns have yet to be developed successfully, and this area will be the focus for the remainder of this thesis.

Chapter 3: Mechanical and ergonomic design of the reader

3.1 The Conductive Tip

3.1.1 Previous work in this area

In the preceding Paper++ project, two different conductive tip configurations were utilised. One configuration comprised a single contact point using the conductive tip, with the user's hand creating the conductive path to the paper, as shown in Figure 2. The single-point configuration was subject to variations in users' conductivity, and their contact with the pen and conductive coating on the paper.

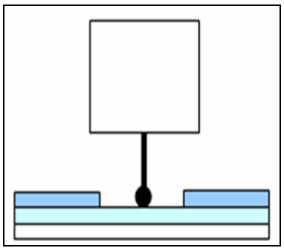


Figure 10. The single contact tip configuration.

The other tip configuration utilised two closely spaced contact points, with a minimal conductive path between them, hence eliminating the need for creating the conductive path by the user.

3.1.2 Investigation into electrical and physical robustness of tip configurations

In the early stages of the project, the decision was made to adopt a two-point contact configuration, because it was considered to be electrically more robust than the single-point contact. The two-point configuration was electrically similar to the previous Paper++ model; however, the contact tips were designed to be more compliant in use.

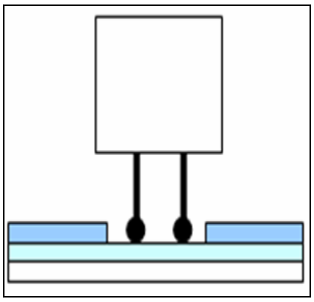


Figure 11. The parallel-tip configuration.

The tips in both the single-tip configuration and the parallel-tip configuration were formed from gold-plated contact probes (Ingun “05” bullet nose), originally designed for circuit testing. The probes were telescopically sprung, which allowed some compliance along the length of the probe, as well as laterally.

3.1.3 Evaluation of the parallel tip design

The parallel tip configuration had a low abrasive impact on the prints, and as the position of the tips could be seen, it was easy to align them with the printed patterns; the swipe results were best with this configuration. However, the configuration was vulnerable to damage, and had to be dragged, rather than pushed.

3.1.4 Design of concentric tips

A concentric tip was built, to test the option of using one sprung probe within a conductive sheath as shown in Figure 9. The design was electrically identical to that of the parallel-tip probes, in having two points of contact, but improved on their physical robustness.

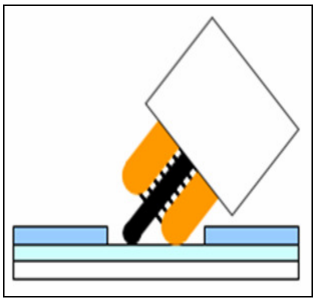


Figure. 9. The concentric-tip configuration, electrically identical to the parallel probe configuration.

The outer sheath was not a perfect hemisphere or ball-nose, but rather a flat-topped cone, which had been rounded off close to the centre hole. Turning a brass bar down to a conical tip, and then rounding the outer edge, created the tip's sheath. Brass was selected due to its ubiquity of use in electrical contact mechanisms, ease of machining, and resistance to corrosion.

3.1.5 Evaluation of the concentric tip design

This configuration significantly increased the lateral stiffness of the tip, due to the centre probe being supported by its surrounding sheath. One problem with the concentric-tip configuration was that the larger radius of the sheath had an effect on the readable resolution of the pattern. If the sheath is too wide, then the pattern must be scaled up for the geometric distortion to be minimised.

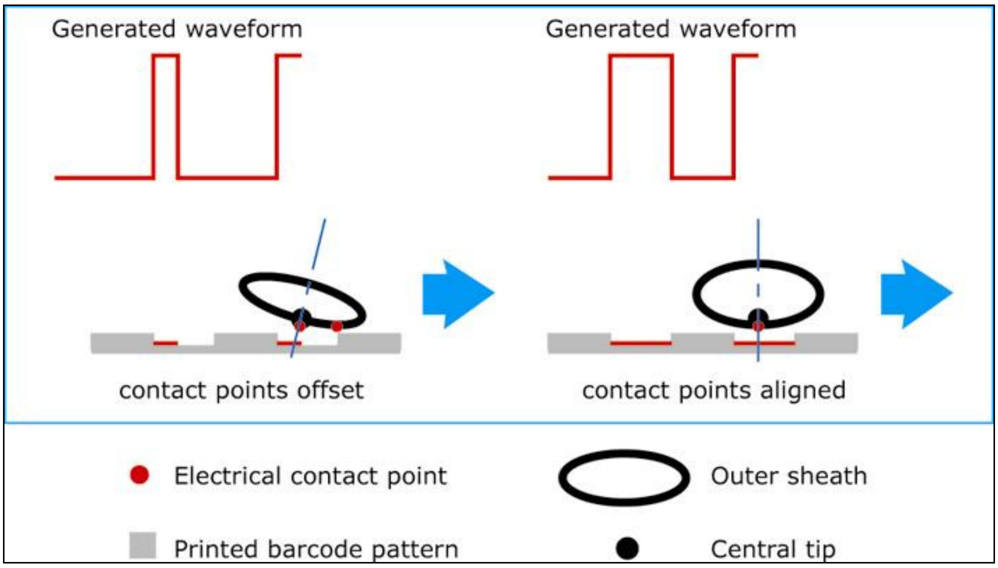


Figure 10. Effect of orientation of contact tips, with respect to paper, on generated waveforms.

On inspecting the paper after each swipe test, it was evident that the impact of the electrical contacts had a markedly degrading effect on the pattern. Swiping on a clean swathe of pattern nearly always yielded a good result with both configurations. Once wear began to build up on the pattern, the results were less successful. What was possible to infer from results, is that if the impact of the contact point could be minimised, then there was potential for a higher repeatability of swipe success rate with the single-point configuration. However, the concentric-tip design was relatively inflexible, orientation sensitive, and caused damage to the paper (see Figure 11). The outer sheath caused more damage than the central (sprung) tip, due partly to the small contact area, and the fact that the user could press the reader (and thus, outer sheath) as hard as they liked against the printed medium. The central tip also damaged the paper, as it had little lateral flexibility; even though it was able to flex along its length, the dragging of the tip did not properly utilise the inbuilt spring action.

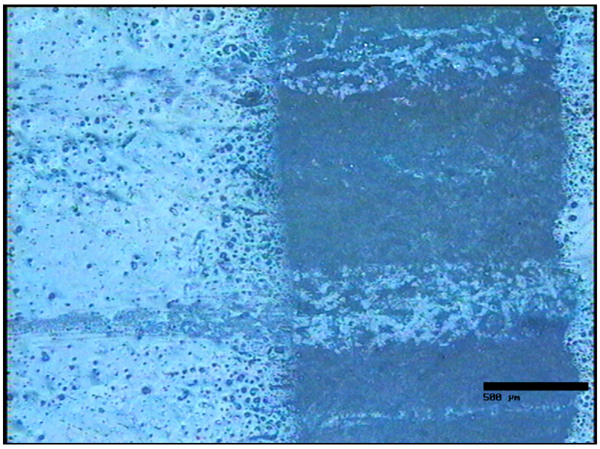


Figure 11. Effect of conductive tip configurations on printed lacquer when using the concentric tip. Lacquer mask is lighter bar. The white deposits on the dark bar are lacquer material scraped off by tip contact.

3.1.6 Fully floating concentric tip design

Following a semi-automated test series, it was decided to make further improvements to the concentric tip design. A computer model of the reader body design was created in ProEngineer Wildfire software, and converted to a format suitable for processing by the fused deposition modelling (FDM) machine. The FDM model, created from ABS plastic, was designed to hold the tethered sensor board of the development PCB prototype, and to act as a test piece for a future complete ergonomic package.

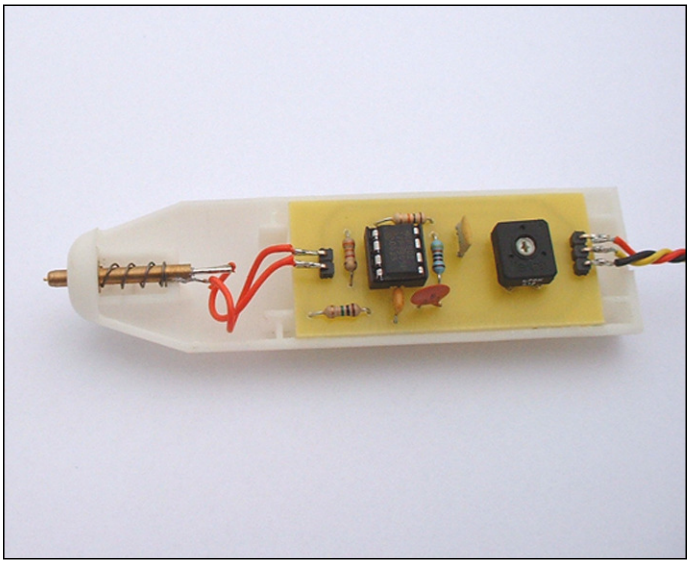


Figure 12. Tethered prototype with fully-floating concentric contact tips.

A solution to the issue of pressure damage was to have both the central tip and the outer sheath 'float', with the main contact pressure point being moved to an annular ring around the two (Figure 12 * ARABIC l). The outer ring had a generous radius, to minimise contact damage to the substrate. The two concentric electrical contacts could then be independently sprung, similar in principle to a telescopic fork on a motorcycle, so minimising their impact on the printed medium. The area of interest was the large contact radius of the outer support, and how this would affect the use of the prototype reader.

3.1.7 Evaluation of the fully floating concentric tip design

In initial testing, the physical impact of the plastic outer support ring was minimal. The two tracks left by the passage of the contact points were less damaging than those of the earlier unsupported concentric-tipped prototype. The outer concentric tip did still leave a slightly deeper track, but could be remedied by changing the spring rate behind it. There are bound to be usage marks, as this is a contact device, and too low a contact pressure might also be detrimental in terms of signal quality.

3.2 Synthesis of tip designs: the cantilever tip

A significant issue arose, when it was discovered that the user could directly affect the proportions of the generated waveform, by their handling of the pen-like reader. Due to the orientation issues with the two-point design, the decision was made to adopt the single contact point electrical design, with the user providing the second contact and electrical path to the reader. The hardware solution (Figure 13) was to merge the two designs: the vertically oriented (concentric-tip) probe, and the dragged (parallel-tip) probe.

The concept was first tested on the prototype tethered PCB sensor board, constructed from nickel-plated copper wire, and functioned acceptably. It was packaged in the flat-faced FDM prototype (Figure 15). However, these wire cantilevers were not stable in use. The next stage of the cantilever design was a short beam, made of brass shim, with a dimple punched at its free end as shown in . The brass shim was 0.2mm in thickness. The punch used to create the dimple had an included angle of about 90°; if its point can be considered sharp, the raised feature on the other side of the plate had an ideal diameter of 0.4mm (likely slightly larger). In comparison, the sprung probe contact hemisphere was 0.6mm in diameter.

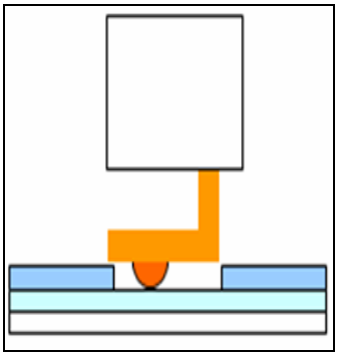


Figure The cantilever-tip configuration

The cantilever design allowed the contact point to flex, and so maintain pressure on the swiped substrate. The cantilevered plate was also far less susceptible to digging in, as there was no change in its ‘angle of attack’, regardless of the direction of swipe. The plate had high lateral stability, preventing it from digging into the substrate and skipping, so reducing errors in the output waveform of the sensor. The flex in the sprung probe meant that it would not follow the movement of the reader body rigidly, which improved its compliance with the paper. For a more complete test of the concept, a fully integrated prototype was required.

3.3 Discussion on influence of tip configuration

All the contact tip configurations could be used with the lacquer-masked printed structure; each had advantages over the other, but the compromise solution of a single contact tip was selected for the later prototypes as it removed the greater variability of user interaction from the system.

The parallel-tip configuration did not require hand contact with the conductive paper. This obviated whatever electrical problems were incurred by hand-holding the reader, and was electrically independent of the users' interaction with the conductive coating. The electrical robustness was countered by the sensitivity of the two contact tips to orientation, with respect to the printed pattern. The orientation issue caused more failures than electrical contact itself.

The single-tip configuration relied on the user holding the paper with one hand, and drawing the device across the printed patterns with the other. Due to the effects of the user and the ambient humidity on the paper, a good conduction path between hand-to-paper and pen-to-paper contact was not guaranteed. However, the performance potential of the single-tip configuration was that there was no user- geometric distortion of the generated pattern waveform, so that it was expected to be substantially similar to the proportions of the printed pattern, giving a greater decoding success.

3.4 Appraisal of lacquer masks and conductive substrate.

Substrates and coatings were first evaluated by visual inspection, due to their swift deterioration. Subsequent developments improved the quality and durability of the lacquers and substrate. Although the performance of the printed samples was never fully characterised, each sample was tested by comparing the performance of each with a set number of swipes, with a particular sensor tip configuration.

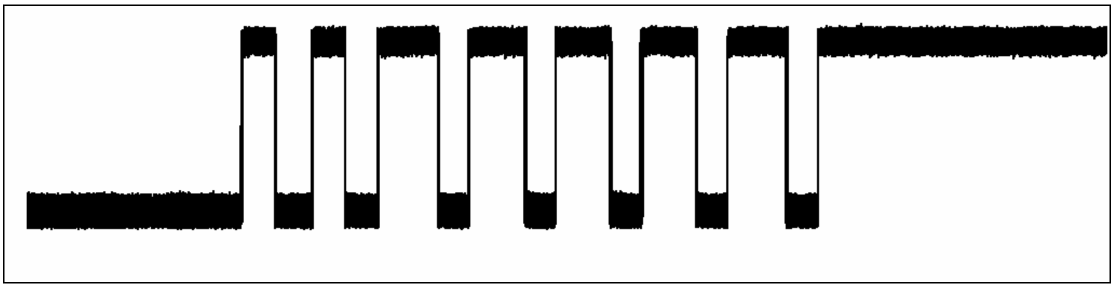


Figure 12. UVD00100-405 masked original substrate. First swiped waveform.

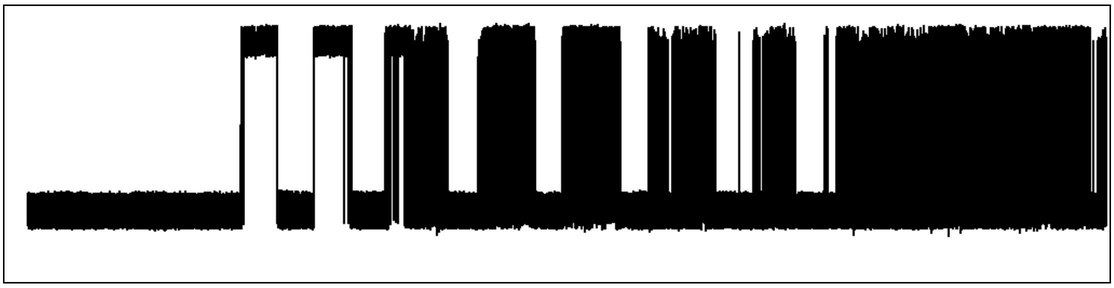


Figure 13. UVD00100-405 masked original substrate. After 10 swipes, over the same path.

Table 1 is indicative of the type of test result and evaluation of both reader contact tips, and print samples. There were many permutations, and the results were assessed in order of perceived performance, with regard to signal quality (stored on digital oscilloscope) and wear characteristics of the lacquer mask.

	Modified Parallel-tip	*Parallel-tip*
1	UVD00100-405 06/02/06	*UVD00100-405* *06/02/06*
2	Multi-print 090 06/02/06	*UVIbond_UV383* *06/02/06*
3	UVIbond_UV383 06/02/06	*RD2354* *06/02/06*
4	UVD00100-405 24/01/05	*Multi-print 090* *06/02/06*
5	RD2354 06/02/06	*UVD00100-405* *24/01/05*

Table 1. Reader tip matching to lacquer-masked conductive paper.

Later paper and print samples improved, such that evaluation could be promoted to pattern decoding success, rather than mere physical durability. With the decoding evaluation, larger sample sets were tested, and quantifiable data logged (Chapter 7).

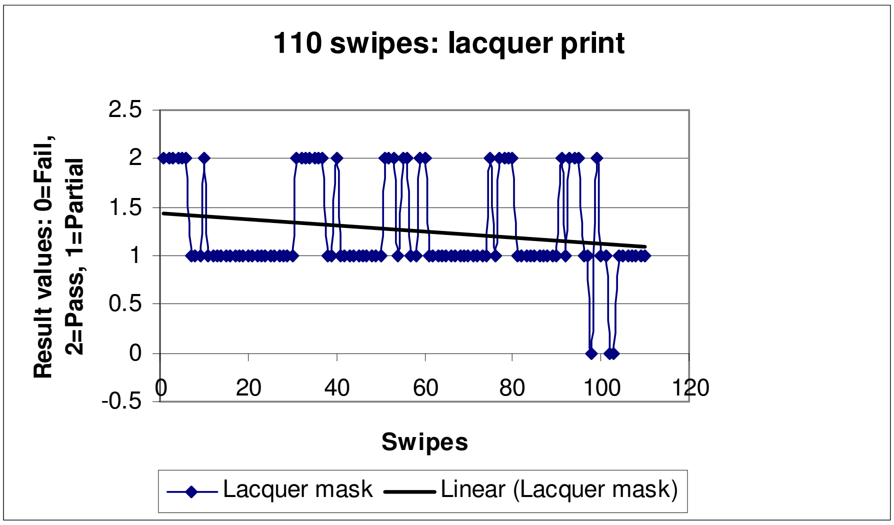


Figure 14. Typical later quantifiable assessment of print sample. Trend line indicates wear.

3.5 Ergonomic design of reader casings

Figure 15 shows the first full prototype of the tethered barcode readerFigure 14 first configuration of the. . The contact tip configuration was concentric. It successfully demonstrated the integration of signal processing and decoding hardware, packaged within a commercially available marker pen body.

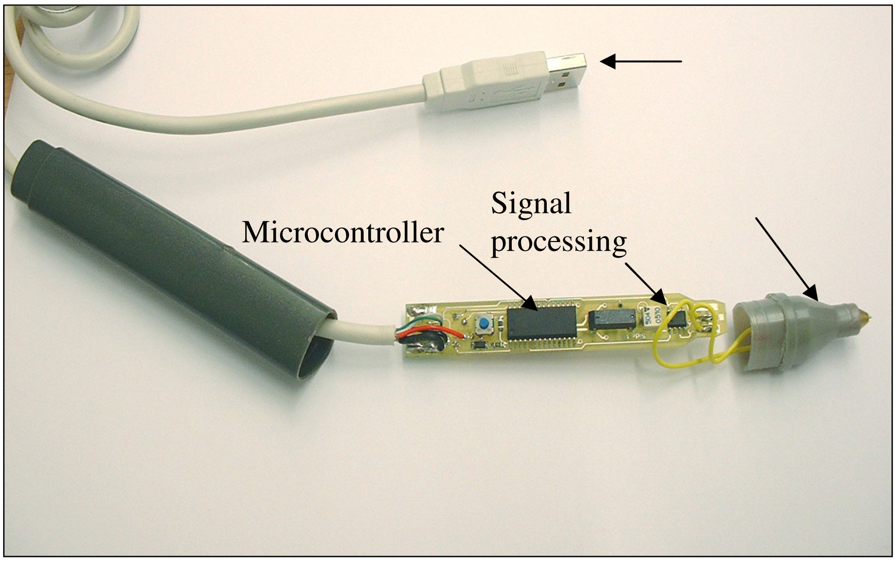


Figure 15. The components of the USB tethered barcode reader.

.User tests had indicated that the pen style of the tethered barcode reader had caused confusion for the first-time users, due to their expectations of using it like a pen. As the reader is not a point-specific device, and more an area-specific device (due to the low resolution of the patterns), it was suggested during discussion with a Professor of Ergonomics within the University that an alternative to the pen style could be a mouse-like device. The implications of this were that the user would be encouraged to orient it flat against the paper. The broader, ‘unfocussed’, base of the reader would reinforce the sweep motion required, and avoid direct comparison with pen-like devices.

A potential problem with a larger flat footprint (eg. PC-mouse sized) is that there is no guarantee that the paper will be supported on a flat base. If the paper is part of a book, either folded open or held by hand, then the curvature of the paper in one or more planes would cause handling problems. The compromise solution would lie in emphasizing the full-face placement of the reader, without exaggerating it physically.

The physical limitations of the interface would remove many of the problems associated with pen orientation. Ensuring that the contacts are held correctly against the paper would be crucial to the read success.

A related issue with the contact probes was that they are necessarily delicate, and the requirement for them to protrude from the reader face makes them vulnerable to damage. A solution to this problem was to hinge the entire contact face of the reader. The concept is similar to that employed in some computer mice, in that the upper body is depressed to ‘click’.

To test the concept, a new model was constructed which had a flat contact face (Figure (Figure 15). To ease movement over the paper, two small rounded studs were formed at the ‘upper’ corners of the contact face. This created a three-point contact footprint, whilst effectively maintaining the integrity of the original concept. In the case of the flat-faced reader, depressing it brought the flexible probes (within the body) into contact with the paper, only during use. When lifted away from the paper, the face hinged out sufficiently to mask the probes, thus protecting them. This mechanism also ensured that the reader was correctly positioned against the paper for good contact.

Figure 15. External and internal views of tethered cantilevered contact reader.

3.6 First integrated reader design

The first integrated reader design (Figure 17; left-hand side) was an exercise in packaging, not styling. The aim was to produce a contained device, within the smallest physical envelope. Thus, the shape was prismatic, comprising the smallest dimensions necessary to enclose the surface-mount PCB, battery and external contacts.

The external (user) contact was formed from a paper clip. The paper contact was made by the brass shim cantilever. The PCB was a fully-integrated Bluetooth wireless design, built with surface-mount components.

3.6.1 Evaluation of first integrated reader design

The design was successful, in being fully portable, robust and in no way mistaken for a writing instrument. The last point was important, though it did raise the issue of how to suggest the function of the new device, through design of form.

3.7 Second integrated reader design

The second integrated design (Figure 17; middle) was not functionally different from the first, apart from some firmware modifications. The aim was to create a casing form which would be ergonomically contoured, and which would give some hint of its purpose. The affordance of a pen, pencil or marker is such that most people would recognise it, or easily discern its function. With such a novel device as the contact barcode reader, achieving this was more difficult. It was hoped that the hinged face of the reader would be understood as the 'working end' of the device.

The external user contact was created from narrow bands of brass shim, formed to follow the contours of the device's 'waist', and so was not as obtrusive and vulnerable as the wire contact of the first integrated model. The position of the bands around the 'waist' was positioned where the user's gripping fingers would naturally hold the device. The form choice was decided by user testing, from a selection of differently styled maquettes, before the casing design was committed to CAD/CAM.

3.7.1 Evaluation of the second integrated reader design

There were some technical issues with the second-iteration casing design. The major technical issue being that the internal battery compartment was oversize. This, coupled with the flex of the casing in use, often caused the battery to move off its contacts. User trials were interrupted by the intermittent resetting of the reader’s MCU, and were negatively impacted by it. The fact of the loose battery was not immediately picked up as, during initial testing of the reader, knowledgeable and careful hands contrived to keep it safe. Inexpert users, on the other hand, treated the reader as a finished product, and thus demonstrated its weaknesses with immodest ease.

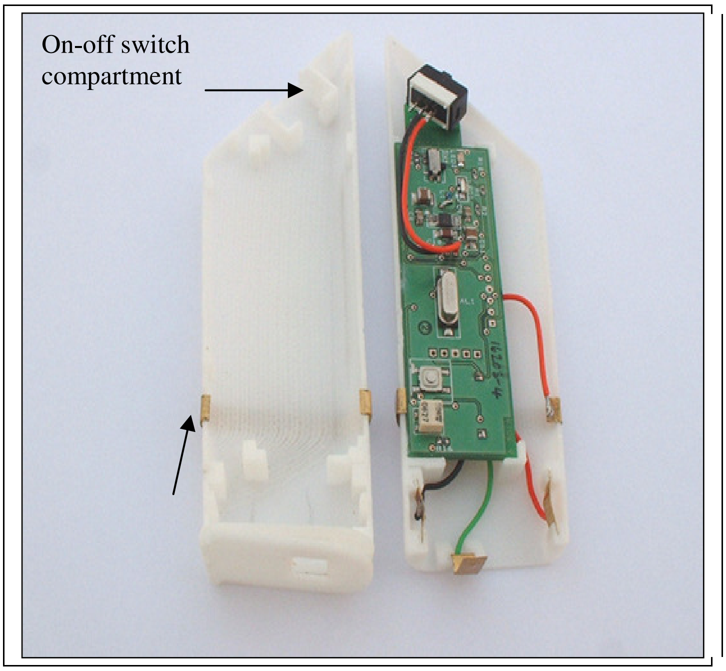


Figure Second-iteration wireless reader, showing internal layout of components.

Other areas identified as being weak were: the power switch, which protruded vulnerably; the external electrical contact band, which was still considered (mostly visually) obtrusive; and the styling of the reader. All attempts had been made to avoid direct comparison with the more sophisticated (Anoto) digital pen in the project group. That was why the contact area was designed to be flat, as described earlier.

The styling of the reader suggested to many users that it was better suited as a pen-type device. This was because the ‘top’ of the reader, opposite its working end, was styled as a wedge (similar to a marker pen). Given that affordance, and in the context of its use with paper, users opted to use the incorrect end of the reader when first introduced to it.

3.8 Final casing design for reader

The third casing (Figure Figure 17; right-hand side) was designed with the previous user study in mind. Areas of improvement were the battery compartment, power switch, external electrical contact, casing rigidity and styling. The battery compartment was resized to suit, thus preventing significant movement of the cell within. The power switch was repositioned to sit flush with the external surface of the casing; it was thus not confused with the functioning of the reader during use. The external electrical contact was changed from a flat brass band to a neater section of nickel-plated wire, and blended better with the finger rest of the reader.

The styling of the reader was reworked, partly as an exercise in packaging efficiency. The newer casing was shorter and slimmer, both factors which contributed to the improved stiffness of the assembly by minimising the amount of enclosed space. Contributing to the smaller size was the use of a more compact PCB layout (Figure 18Figure 18), the functionality of which remained unchanged. The styling ‘wedge’ was replaced with only a very slightly angled end, to break up the rectangular side profile. A light-pipe was integrated into this end of the casing, to transmit the visual signal from the LEDs on the PCB to the user in a more direct manner.

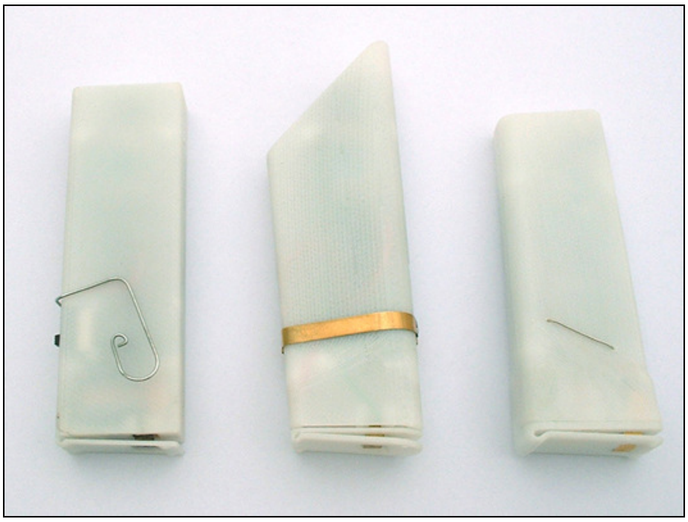


Figure .17 Developmental series of reader designs; the first shown on the left-hand side.

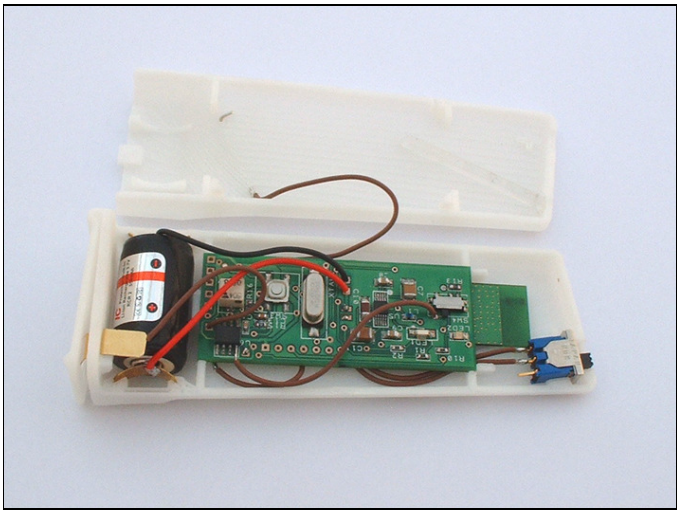


Figure .18 Final barcode reader components and its construction.

3.8.1 Evaluation of final reader casing design

Overall, the new reader casing was considered a successful improvement, having addressed the key issues which so troubled its predecessors::

- battery compartment resized: more compact;
- power switch recessed;
- external electrical contact better integrated: modified;
- casing rigidity improved;
- body styling reworked to reduce false affordance;
- casing rigidity improved by minimising enclosed volume.

Chapter 4: Electronics: signal amplification and processing

The printed pattern is represented by a low voltage signal, generated by contact between the contact tip and the conductive paper. The amplified signal from the pre-processing circuitry is transmitted to the microcontroller for digital processing.

The generated voltage is amplified using a saturated op-amp, and conditioned using an active filter; both functions combined in a MCP602 dual op-amp package ((). The MCP602 op-amp is connected in series with a non-inverting comparator, integrated (and configured) within the microcontroller, to digitise the (analogue) scanned waveform. The gain of the amplifier was made tuneable by using a variable resistor. The gain could then be varied in order to compensate for the variable conductivity of the substrate. The gain was not set to maximum, as that amplified noise due to sliding contact; the values were selected to just saturate the amplifier output.

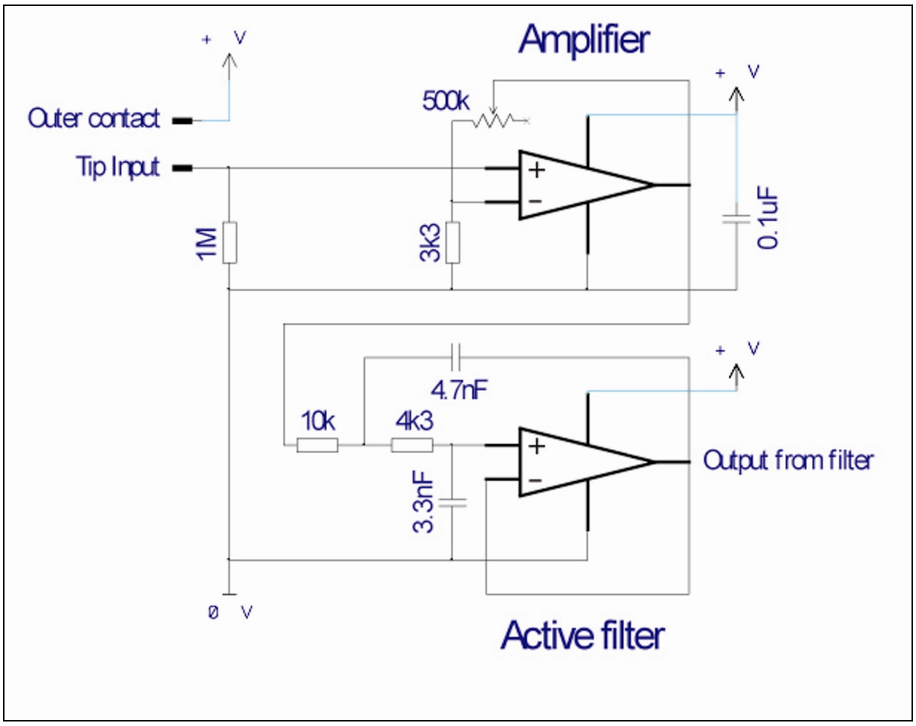


Figure . Schematic of the MCP602 dual op-amp and the active filter.

4.1 Signal filtering

Three different filter set-ups were designed and tested using the input from a real scan:. Butterworth, Bessel and Chebychev active filters were initially tested, using the FilterLab software package from Microchip. The filters were configured as 2nd order, for a 3 kHz corner frequency. The corner frequency was determined by evaluating the swipe waveforms, and deciding on a minimum acceptable frequency for legitimate patterns. The waveforms were compared to determine which had the greatest effect on the output waveform.

The three filters were then subsequently constructed on a breadboard, each in turn. The circuit was powered by a 5V supply. A sinusoidal signal was fed to the input of the filter, from a Thandar TG 102 signal generator. The output was connected to an Agilent 54621A digital oscilloscope, from which values were drawn. The values measured were the rail-to-rail voltage measured at thelevels output from the op-amp (Figure 17).

[Figure 20]. The filter implementation chosen was Bessel, as it performed best in the breadboard trial. The sensor board was tethered to the original main PCB, to minimise changes to the system.

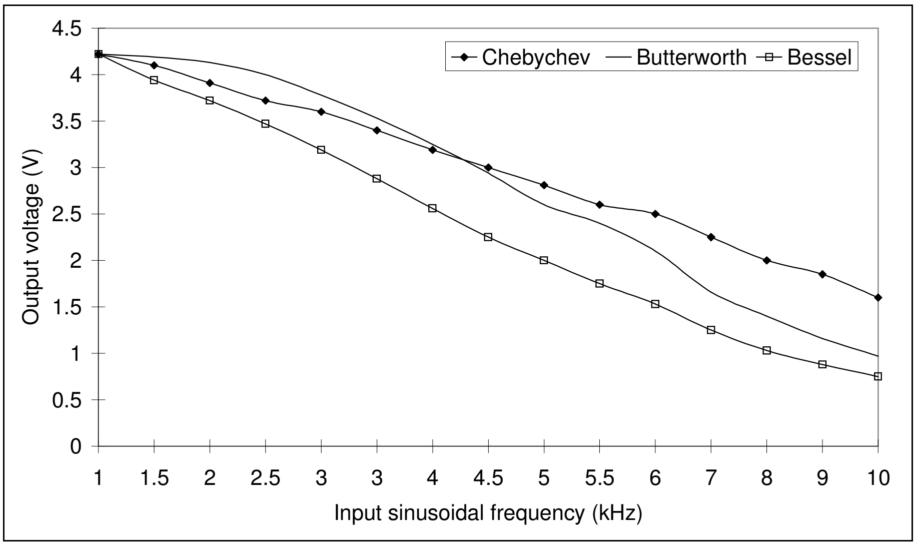


Figure 20. Response of the low-pass analogue filters, 2nd order, 3 kHz corner frequency; as measured.

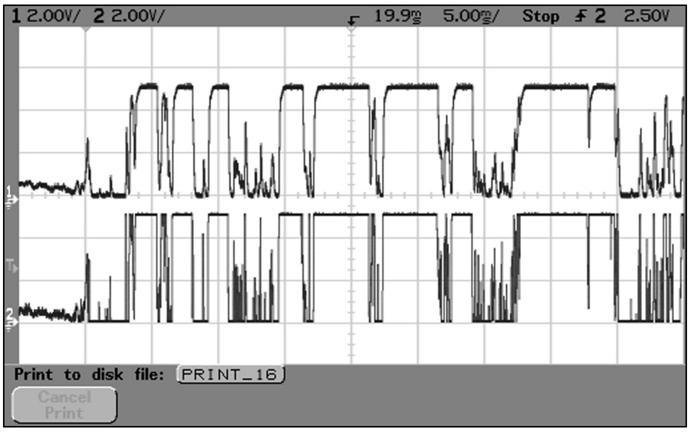


Figure 17. Response of the low-pass analogue filters, as measured.Scanned pattern waveform: amplified (bottom), then filtered (top).

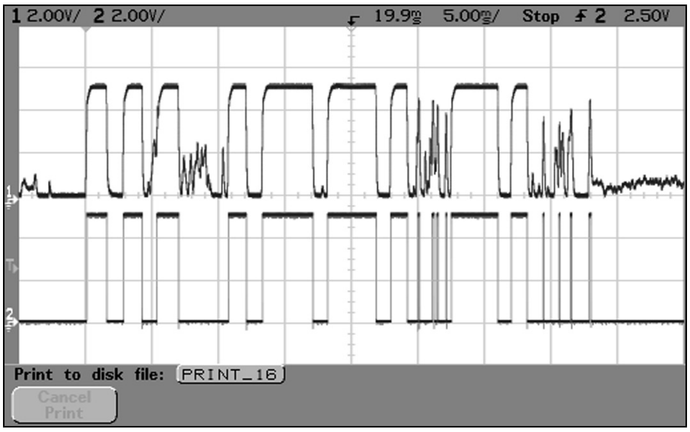


Figure 18. Scanned pattern waveform: signal buffering by comparator.

It is evident that noisy waveforms cannot be entirely saved by the addition of a simple filter. [Figure 17]. What is clear is that in some instances, the high frequency noise, which would have resulted in a string of zero- or low-value bytes, has been significantly attenuated., once the signal was subsequently buffered by the internal microcontroller comparator [Figure 18]. Thus, the fewer digital error values in the set, the less likely that a decoding failure will occur.

The following figures show the effect of both the active filter (Figure 19), and the subsequent digital buffering (Figure 20), on the original amplified signal. The signal was buffered by a comparator configured within the microcontroller, and thus digitised.

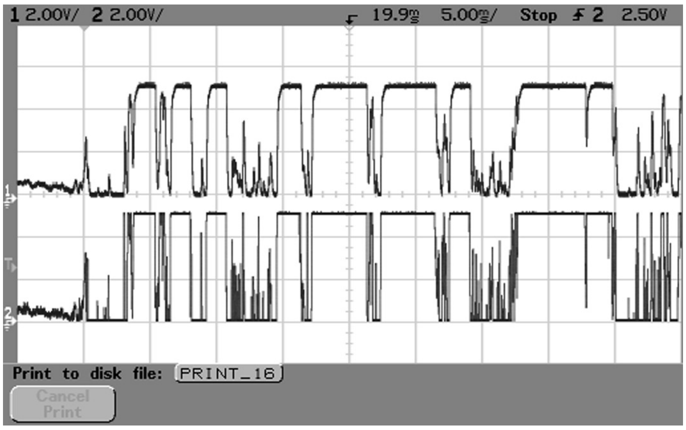


Figure 19. Waveform filtering: amplified (bottom) to filtered (top).

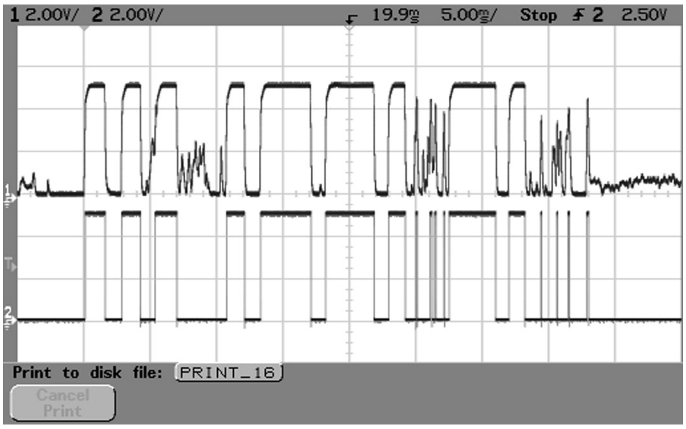


Figure 20. Waveform buffering: filtered (top) to digital comparator (bottom).

4.2 The microcontroller

The microcontroller selected for the first (tethered prototype) PaperWorks reader was the PIC18F4550. It is a multipurpose microcontroller made by Microchip Technologies, Inc. Importantly, the microcontroller has an onboard USB module, thereby eliminating the need for many extra external components required to support the USB communications. The microcontroller supports in-circuit serial programming (ICSP), which allows it to be updated with firmware changes, while connected to the PCB. This made it possible to test code amendments quickly, without the need to remove the PCB from the reader. As the microcontroller was the most fully featured of its product family, it was deemed useful to have all options available at the beginning of the electronic design process.

The specific choice of the PIC18F2550 version of the microcontroller (() used in the first integrated, tethered readerreader was simply due to packaging requirements. It had all the features required of the larger IC, but with fewer IO pins.

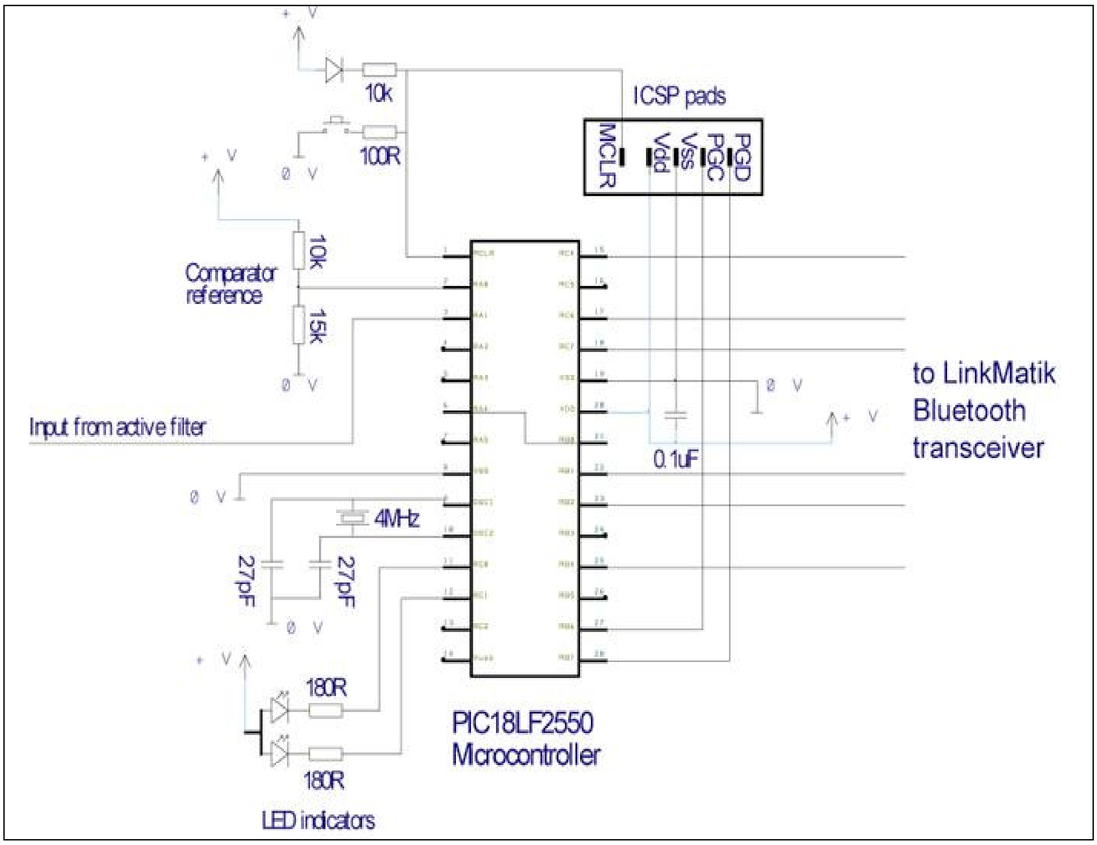


Figure . The schematic of the microcontroller unit, and the external passive components.

4.3 Wireless communications, and hardware integration

The second year of the project required the further development of the reader to implement wireless connectivity. This change introduced new challenges to the electronics design, as the move to wireless communications removed the regulated power supply of the previous USB connection. New issues of portable power supply, regulation and integration were introduced. To this end, the options of wireless protocols and power management were investigated, and are reported in the following sections of this chapter.

4.3.1 Selection of wireless protocols and electronics design

The first wireless device designed and developed used a remote LinkMatik Bluetooth module. Several wireless protocols and hardware solutions were considered, but the most relevant were Zigbee, Bluetooth and ANT. At the time of investigation, Zigbee required a licence fee for its use, and ANT had not yet been certified for use within Europe. ANT promised the best and lowest power consumption, followed by Zigbee. That aside, the predominance and maturity of the Bluetooth system made it a safer choice than the newer, but unknown, alternatives.

The first (tethered USB) prototype with the PIC18F4550 PCB was rebuilt, and configured with on-board connections for the LinkMatik 1 Bluetooth module. The prototype PCB had a connector for external power, so that various power modules could be trialled before any solution was committed to the main board. The large-scale prototype could easily accommodate modifications, at no real cost, unlike a surface-mount board manufactured externally. The main hardware change was that the USB socket was replaced by the 18-pin wide package for the LinkMatik 1 Bluetooth module, with associated pin connections to the PIC18F4550.

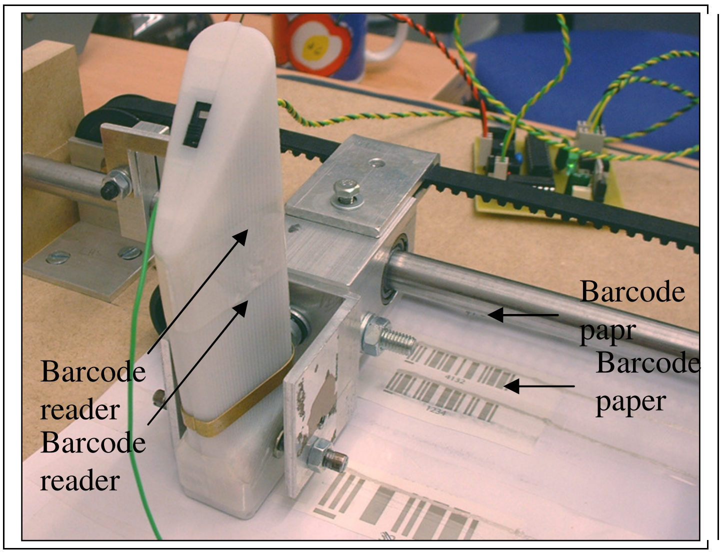


Figure .22 Testing the wireless barcode reader using a purpose-built testing rig.

Firmware changes included removal of the USB-related code and directly addressing the universal asynchronous receiver transmitter (UART) of the microcontroller. This meant that the onboard communication was set up as if the connection was via the RS-232 serial protocol. The virtual communication port established by the Bluetooth driver on the computer end was treated in the same manner as with the USB connection. This eliminated the need for software changes to the existing code.

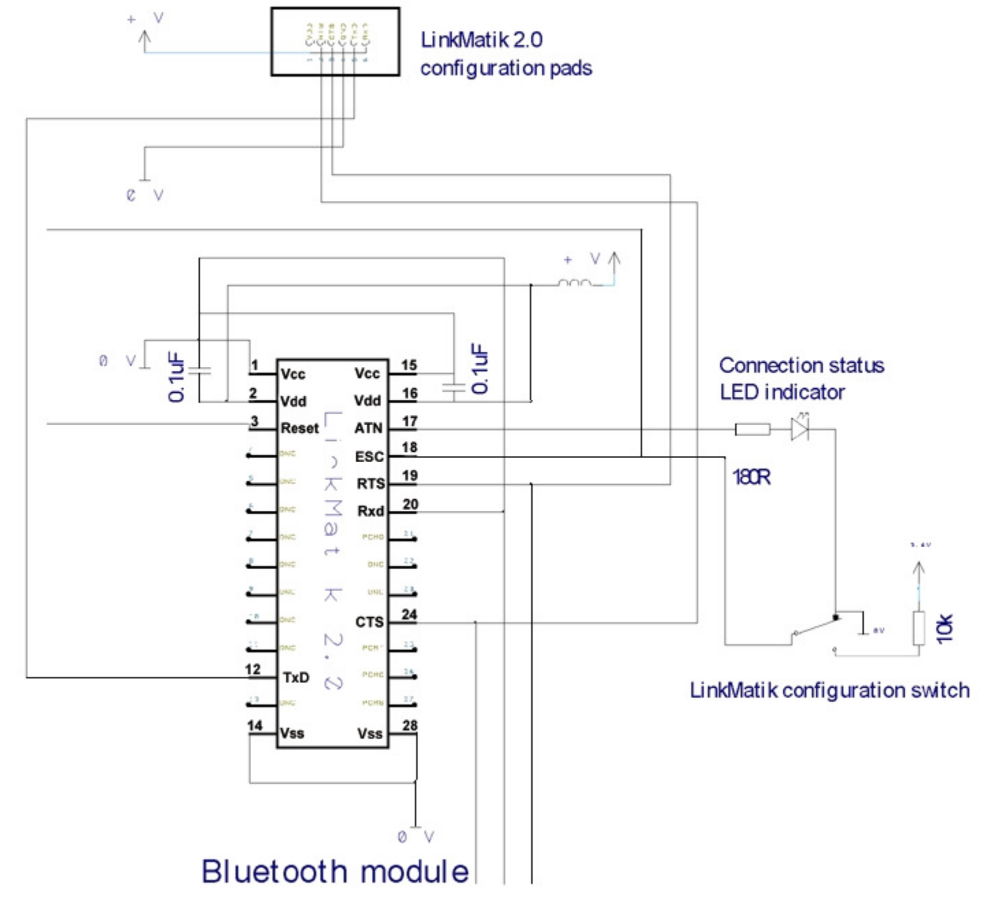


Figure .23 Schematic of the LinkMatik 2 Bluetooth wireless module.

Configuration of the LinkMatik 1.0 had to be achieved via a physical link to HyperTerminal, the Windows RS-232-protocol communications application (, showing the later LinkMatik 2.0 module). The hardware solution was to build a voltage level converter for use between the computer and prototype. To achieve this, a MAX3232 IC was selected (), which required only the use of several passive components (capacitors) to control the output voltage level to the LinkMatik 1.0 module. The converter was connected to the PC by a 9-way D-plug, and to the prototype board by a ribbon cable and single inline (SIL) connector. Connection was first made physically and then electronically by switching the prototype on, after starting a HyperTerminal session (no handshaking – control was automated by the transceiver module). The schematic was changed to include the new connections to the transceiver module.

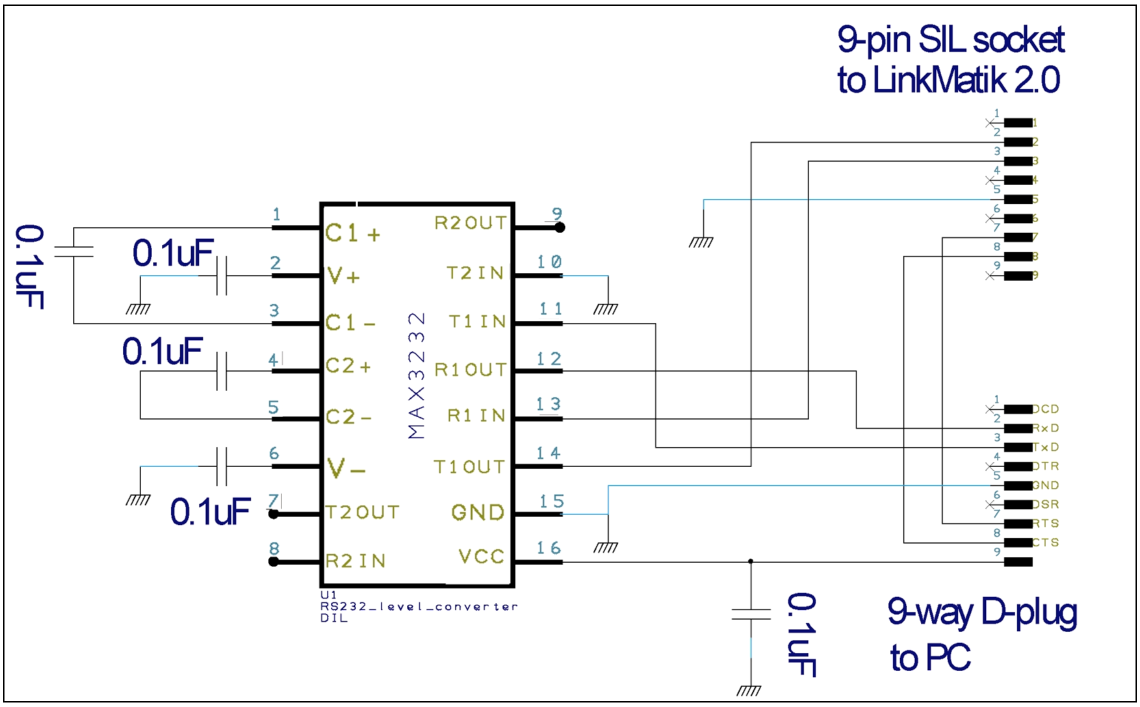


Figure 21. MAX3232 voltage level converter.

4.3.2 Further development of the wireless hardware

The second prototype was developed with the similar functionally as the first prototype, but employing the PIC18LF2550 chip. The important aspect of this chip is that the ‘L’ designates the low-power capability of the IC design, allowing it to function at voltages as low as 2.5V. This meant that the device could be made fully portable, as the power management developed with the earlier board could be implemented on the low power board. The prototype with the PIC18LF2550 could then be translated seamlessly to its surface-mount incarnation. Having changed from USB connection to wireless Bluetooth, the necessary hardware and firmware changes were made to incorporate the PIC18LF2550 without increasing the permutations of possible error. The final hardware prototype is shown being tested in Figure 22.

4.4 Power supply and management

The tethered reader had required no power management, as it was connected to a regulated power supply from the USB port. The wireless barcode reader had to be self-powered. This required the use of batteries, and the option to replace or recharge them. It was decided to use rechargeable batteries, after several considerations:

- Replaceable batteries require more investment in the design of the reader packaging, and more mechanical complexity (battery compartment, removable door, etc.).
- Due to the power requirements of the LinkMatik 1 module (120mA on connection, up to 270mA peak), batteries may need to be replaced frequently, adding to consumable costs.
- From a user's perspective, having to replace batteries may result in the product being used infrequently.
- Integrated rechargeable batteries require less user interaction with the maintenance of the product (no need to open the case, possibly losing the door/lid; no risk of inserting batteries incorrectly).
- Rechargeable batteries can be charged within hours. Not as fast as direct replacement by disposable batteries.
- PCB mounted batteries would bebe more compact than a separate battery compartment, with loose batteries.
- Rechargeable batteries are cheaper in the long-term life of the product.
- Possibility of charging through a USB port, eliminating the need for a charger.

A charging circuit is necessary for the use of rechargeable batteries. There are products on the market which allow rechargeables to be replaced just like single-use batteries, but this again requires separate investment in the batteries and the charger unit. There are charging management chips available which, with the necessary discrete components, can provide all the functionality required for recharging batteries in situ. The adoption of integrated batteries and related charging circuitry would complicate the electronic and hardware design, as a charging dock may be required.

It was also pertinent to keep in mind the nature of the product, which was considered to be of limited lifespan. Although rechargeable battery implementation does seem to contradict the previous statement, it does satisfy one suggested application of the product, which is for educational use. There, the product would be required to function for a reasonable period; even if the lesson was limited in duration, it might well be repeated for different learning groups. A more limited ‘give-away’ version could be fitted with a single-use battery, without the charging circuitry.

4.4.1 Power management using Sleep mode

As well as rechargeable (or not) battery power, the control of the reader activity can have a bearing on the life of the product. If the reader was not being used, then switching it off would save on power consumed by an idle processor and wireless module. Indeed, while the reader is not processing and transmitting data, the power consumed was measured as about 47mA. That is continuous power consumption, over half of which is due to the processor. Shutting the system down (putting it to ‘sleep’) reduced the current consumption to a nominal 1mA.

The idea of sleep mode is that it is practically equivalent to switching the system off, using the microcontroller as an on/off switch. There is no direct disconnection from the power supply, and a quiescent current is always flowing through the devices (MCU and wireless module). Thus, an external event, such as scanning a barcode, would trigger a restart of the system and bring it to full power and activity. The sleep option was implemented to test its real effect on the system.

In the implementation of this mode, it was found that the period of time required between swipe (wake-up from sleep) and transmission of data was about 5-6 seconds. The majority of time taken after wake-up was due to the LinkMatik 1 reconnecting to the PC. In slave mode to the PC, it was discovered that after disconnection (due to the Bluetooth master losing the connection), the LinkMatik module had to be reconnected manually. The author had to watch the indicator light on the module, refresh the service and then reconnect the link between the two devices. This was not an acceptable state of affairs for the system, as the user could not be expected to engage at this level of control.

The LinkMatik 1 was reconfigured as a master device. This allowed it to actively seek a connection if it was disconnected. As it was also configured as monogamous, and programmed to look for a device bearing the name of the Bluetooth dongle, connection to the PC was assured. When reinstated into the system, the reader was able to actively reconnect after waking up from sleep. The net result of the reconfiguration was that the process of setting up the system for use had been greatly simplified, without loss of functionality.

The user experience of the wake up from sleep was a delay, before the results of their latest scan were displayed on-screen with the VB6 application. The delay caused some confusion; due to the requirement of accommodating a range of swipe speeds, the lowest speed swipe relied on the reader 'waiting' for a second after the completion of the swipe. The lack of direct response, coupled with the reconnection delay after sleep, took far longer than users expected. During the testing stage, the sleep function became an irritant; in the course of using the device, it would often go to 'sleep'. Thus, there were many instances where the initial swipe after a period of inactivity would require some time to register. With sporadic use, the overall impression was that the system was very slow. While clearly a useful application in terms of power management, the sleep function was not carried through the further development of the reader.

4.4.2 Battery selection

During the development process, the prototype board was powered externally, at a nominal 5V (Thurlby Thandar PL154 power supply). This suited both the MCU requirements, and those of the LinkMatik 1 Bluetooth module. The LinkMatik 1 (discontinued at the time of writing) had a stated input range of 3 – 5V, which made it more flexible when selecting power sources. The lower voltage was claimed to affect the maximum transmission distance, but as the reader was expected to operate locally (as opposed to 100m away from the PC), that was not considered a serious restriction.

Appropriate battery technologies in that lower range (~3V) are NiMH, NiCd (both utilising multiple cells to make up the required voltage battery) and Lithium-Ion. Li-ion is known to have the greater energy density – this comes at a higher financial cost, and is also more critical in charge/discharge management. There are many different chemistries in the lithium range, which creates a wide range of cell voltages. Lithium-polymer batteries are an advancement of Li-ion technology, and are regarded as having the highest energy density of the group. However, these are not available in generic cylindrical packages, or similar shapes. They are used in mobile phones, for example, where their construction is adaptable to suit the packaging requirements of modern devices; commonly flat, rectangular packages. During the prototyping stages, it was accepted that a compromise design would use available battery packages.

Initial experimentation took place with a three-cell NiMH battery, which had a nominal voltage of 3.6V. The rated constant current output was low (80mAh), with a rated peak output of 140mA. This was considered just adequate for the indicated 120mA consumption of the reader when connecting.

	NiCd	**NiMH**	**Li-ion**
Cell voltage (nominal)	1.2	1.2	1.5 – 3.7
Energy density	3rd	2nd	Best
Life cycle (charges)	This is dependent on the battery usage, and is affected by deep discharge cycles (shorter lifespan).		
Cost	Lowest		Highest
Toxicity	1st		
Self-discharge * (% per month)	15-20	30	2-3

Table 2. Commonly available battery-types comparison [Error! Reference source not found.**].**

The table above is very general indeed. It is intended as an overview of the available chemistries, and a simplified guide to why the NiMH battery option was originally selected. The toxicity of the NiCd, together with its lower energy density, effectively ruled it out of contention. This is what won the case for NiMH: its accessibility during prototyping. The production version of the reader, if that developmental stage was reached, would benefit from volume bespoke Li-polymer battery production.

The trial NiMH battery (3/V80H) did not last very long in use. The rated 80mAh had a continuous load of nearly 50mA during use. This is where a 'sleep' function would be valuable, but the Bluetooth module in use (LinkMatik 1) took too much time to reconnect.

Li-ion rechargeable batteries were sourced as an improvement, in the CR2 package size. The CR2 is the smallest, at about Ø15mm x 27mm long. The major concern with Li-ion is their stated sensitivity to charging, and possible explosion risks. NiMH does not carry the same risks.

The cost of a single rechargeable Li-ion battery and charger was about £9.90 (www.picstop.co.uk); this was purchased as an intermediary solution to the power supply requirement. Some consideration was given to the issues of internal charging of the reader battery. However, the added cost and complexity of managing the charging cycle of a lithium battery, and building the extra docking hardware, was considered secondary to the aims of the project.

What was important to the project was the fact that the final requirement was for a wireless barcode reader. As such, there was no specific necessity for a bespoke internal charging module; the device could be developed further by an external manufacturing group, or end with the termination of the project. For testing purposes, it may well be the case that the user requirements for maintaining the device are not included in the results. As such, the best course was that which was most expedient. At the time, certainly an external charging unit and replaceable rechargeable battery was the easier option.

4.4.3 Integrated wireless power management

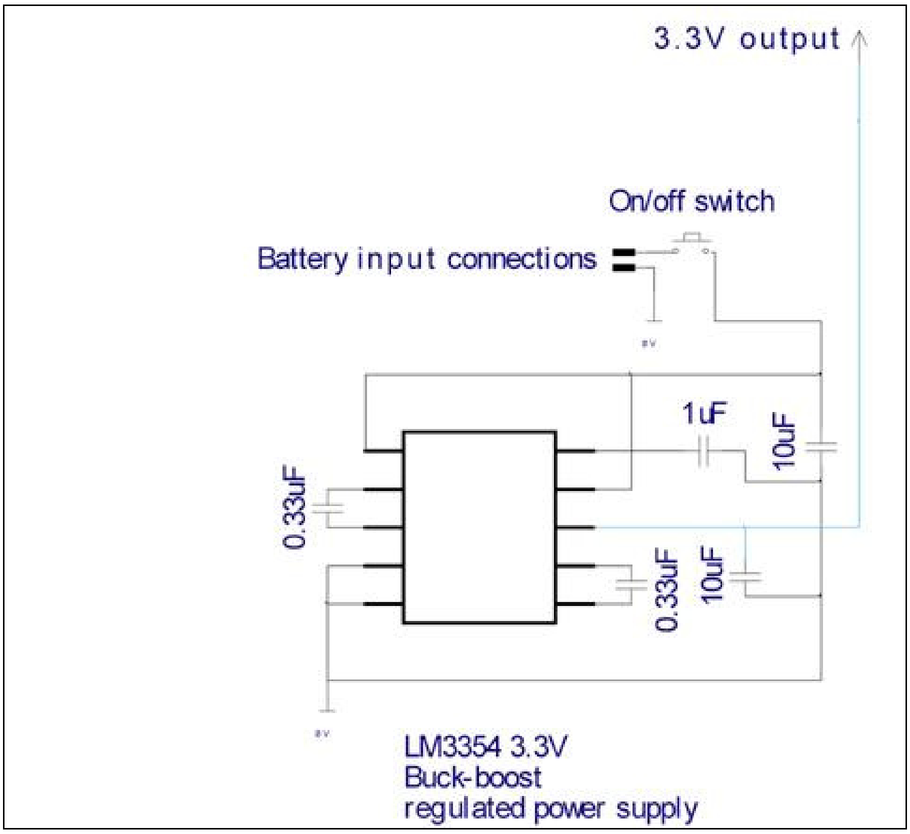


Figure .25 3.3V buck-boost voltage regulator.

The replacement of the LinkMatik 1 Bluetooth module with the LinkMatik 2 was significant in that it demanded a strictly controlled input voltage; nominally 3.3 V, within the range of 3.2 – 3.4 V. The signal levels to the device had to conform to this voltage, which meant that the MCU either had to operate at the same voltage, or interface with the module via a level shifter. It was deemed simplest to power the entire circuit at 3.3 V, which required a voltage regulator.

The input voltage from the battery was variable. An alkaline disposable battery has a nominal voltage of 3 V, and a rechargeable Li-ion, 3.6 V. However, the unloaded voltages are about 3.2 V and 4.2 V respectively. The voltage levels were not sufficient to use a standard voltage regulator, as these require a forward voltage of around 0.7 V. Some low-dropout voltage regulators require less forward voltage, but the greatest difference between a fully charged unloaded cell and the output voltage is (4.2 – 3.3) 0.9V. The difference was considered too slight, given that the initial loading of the battery might cause the regulator to fail.

The choice was made to use a buck-boost regulator (). This accommodated variability in input power voltage, and was implemented successfully. The regulator functioned until a measured battery voltage of 2.8 V. Of interest, is that as the regulator consumes more current as the input voltage (from the battery) falls, the positive loop condition causes the drain on the battery to increase.

Chapter 5: Software and firmware development

5.1 Introduction

The firmware for the reader, and software for the interface application, were developed together, as they are required to work in synchrony. The development task for the firmware was divided into two parts: communicating with the computer, and decoding the scanned pattern. The development task for the PC software was to establish communication with the device, and then to utilise the communicated data. The PC communication system was created first, as the USB functionality was confirmed using demonstration firmware from Microchip. The interface application was more than purely a demonstrator of the reader's functionality; the application was designed to report on the data sent to the PC from the barcode reader, so that the reader could be tested in real-time. In later versions, the transmitted values were saved to a log file, so that a pattern of results could be analysed.

The wireless reader of the second (project) year was to be a development of the tethered design, which meant that whatever format the transmitted data was in, to the PC in the first year, had to be compatible with a wireless format in the second year. Reliability was a concern, and it was decided to decode the swiped pattern within the reader, and output only the decoded data. This would simplify the wireless transmission issues, as there was a concern that a bad wireless transmission would cause data corruption of a large set of values.

5.2 Software interface

The design language selected for the software interface was Visual Basic 6 (VB6). The code is a high level language, which means that it is simpler to construct a program, due to the syntax being closer to a recognisable language. The lowest-level code language, in comparison, is machine code, which is a notionally incomprehensible string of zeros and ones.

The VB6 design environment has plug-in modules, which simplifies the task of opening communication channels between the PC and a peripheral device, as well as creating a graphic user interface (GUI). The interface between the VB6 program and the PC's operating system is handled invisibly, by the application program interface (API), which reduced the burden on the programmer.

All major development work was done on a PC running the Windows 2000 operating system (OS). The first stage was to develop a basic GUI, and interface the application with the conductive-pattern reader device. The MSComm plug-in module within VB6 allowed a quick start on the project, as it interfaced between the GUI and the hardware connection to the PC. The design intent was to firstly confirm that the correct communication (COM) port to the device was open, and then to receive decoded pattern values as required.

The application required that the device be physically connected to the PC, prior to running the COM check. The process was necessarily procedural, as a bespoke driver could not be written to handle the linking of application and COM port in the background. Thus, the system was not 'plug and play' as commercial systems are. The application automated the COM confirmation process, by a form of handshaking.. Each COM port was checked to ascertain if it was open. If not, then the port was opened, after which a specific byte value (eg. "2") was sent to the COM port (and so to the device, if it was connected to that port). The (microcontroller) device was designed to wait for the initial transmission of the confirmation byte, and if confirmed as the correct value, to return a byte of the same value. If the software application received the correct value byte in return, then it would confirm that the COM port in question was the correct one. The application and the device were then free to continue to the next stage of their programmed routines.

When the VB6 executable file was later run on a machine with the Windows XP OS, the automated COM routine failed to function as expected. Although never resolved fully, the understanding was that the issue lay with the new API; Windows XP retained an association of the last COM port used with the device, and automatically assigned that port number to the recognised device when it was reconnected, even though a physically different port was used. As the author was unable to write a Windows driver program, the solution was to manually select a COM port, based on the experience of which physical connection actually functioned on a XP machine, regardless of the indicated connection.

It can be seen then that the two programs – software and firmware, had to be written with reference to the other, and within the same time-frame. The basic transmission routines were checked independently by the use of Hyper Terminal, a standard communications application found on Windows PCs. Thereafter, the two programs were tested in concert.

Several test and demonstration applications were written, depending on requirements. They all used the same communication set-up routine, whether the device was a tethered USB, or Bluetooth wireless. Both the USB and the wireless devices were configured as virtual COM ports, which in essence meant that the PC recognised them as standard serial devices. This ‘standard’ configuration has been retained by developers of USB and wireless device manufacturers, to allow ease of portability of mature systems to the newer communication hardware. All that was required was, in the case of the USB device, a driver file for the Windows system to recognise the profile of the device.

The final VB6 program was written to demonstrate two devices connected to the application at the same time. The Bluetooth wireless device (barcode reader) transmitted decoded data to the application, and the application transmitted a response to a USB device, which activated a printed electro-chemical display on the same sheet of paper as the barcode pattern.

5.3 Microcontroller firmware

The microcontroller firmware was written in Microchip’s MPLab integrated development environment (IDE). The USB protocol is very complex, but the USB-specific firmware code was available as a stand-alone application from Microchip’s website[32]. The availability of the application code made the use of the selected microcontroller possible, and simplified the initial set-up.

The non-USB application code was written mainly in the “C” programming language. This is an intermediate level language; not not modular like VB6, but still capable of encapsulating complex operations within a line of code, eg. *“if (x > y)..”* The IDE allowed the use of Assembly language in addition to C. Assembly is a low-level language, designed to perform bit-operations as well as byte-operations. It is a level above pure machine code, or binary. The use of C was predominant, but Assembly was integrated wherever convenient.

5.3.1 Initialising the microcontroller

The initialisation process, which is a necessary and preliminary procedure during start-up, is a list of commands which defines input and output states, and modes of operation of the MCU. After initialisation, the MCU waits until the byte swap has confirmed connection to the host PC, via the USB or wireless module. TheThe procedure is active once only, after which the conditions for its running are no longer be valid. Thereafter, communication is one-way only, from the reader MCU to the PC.

5.3.2 Basic swipe reading and decoding structure

The main data processing algorithm was split into three discrete sections. These were named "*read()*", "*glitch()*" and "*write()*". The algorithm was designed to be triggered by an external interrupt, which occurred when the reader first made contact with a conductive artefact. As the reader is swiped across the barcode pattern, the generated input signals are buffered by the PIC. A set of values is stored in sequence by the "*read()*" routine; each value forming part of the waveform sequence, and total time taken to swipe the pattern.

The "*read()*" procedure interrupts the main program when a scan is detected, and stores consecutive data values in an area of memory set aside for this task. The first byte of data always relates to the initial contact with a conductive part of the barcode pattern, and represents a high-level voltage signal. Subsequent values correspond to the input waveform, which alternates between high and low voltage levels. The signals have been buffered through a comparator, so there are only two voltage levels defining high (Vdd) and low-level (Vcc) states. Every value represents the duration of its respective input voltage level in the waveform, but not the level itself. The voltage levels (either high or low) are inferred only by their position in the data set. Thus, the data set represents the input waveform, in terms of sequential timing values. Summed, the values represent the total duration of the swipe. Once the input flow has ceased, the procedure ends.

5.3.3 Removing noise-derived data values

The second, and most problematic procedure, deals with the individual values in the data registers. Due to imperfect contact between the contact tips and the paper, during a swipe, false values can be generated in the data stream. These false values are referred to as glitches, hence the second procedure "*glitch()*".

Starting at the first data value (position '0'): this is known to be a 'high', or conductive printed part of the scanned pattern. Every second value after this is seen as a high value too (as the bar pattern is made up of alternating conductive/non-conductive blocks), with most glitches occurring as 'highs' in the 'low' (non-conductive part of the scanned pattern). With the start position known, keeping track of the relevant 'high' or 'low' characteristic of the data values is easier. Thus, assessing every second value makes it easier to spot a glitch, as the value will be far lower than the preceding one (an absolute relation), or equal to zero. Some glitches are represented by zero-value bytes, but as they occupy a real position in the data set, those byte have to be removed too.

5.3.4 "Glitch" procedure

The data set is assessed by comparing adjacent odd or even-numbered bytes (representing conductive or non-conductive bars in the barcode pattern). The total number of bytes in the data set is known, and this value is used in several copy registers to keep track of various looping routines during the procedure. After a glitch has been discovered and corrected, the main procedure is reset and restarted. The reason for this is to simplify the management of the data set, as the removal of glitches reduces the data set, and thus requires the main counter values to be adjusted to suit.

A 'glitch' value is defined as being between 0 and 15. The value may be considered arbitrary; during the development of the algorithm, the values of the barcode pattern bars were recorded, and those of glitches too. From that experience, a range of values was selected which defined a glitch period, as they were relatively smaller than the values of fast-scanned bars. The solution is imperfect, and a relative association would have been better. However, there is no way to determine a relative value, as the bar width (or period) values cannot be defined until the data set has been repaired and adjusted; a start had to be made.

When a lowlow-value byte is found, a counter is incremented to keep track of all movements following this discovery, with regard to the main count of checked registers, and the position of the checking routine within the "glitch()" procedure. This is the loop routine where every second consecutive value is checked until a ‘normal’ highhigh-value byte is found. The ‘high’ and ‘low’ values refer to the relative values for a bar and a glitch within the bar.

The relevant code snippet for the glitch detection is as follows:

```
“.. if (value1 <= difference) //Set to 15 initially. Absolute, but //arbitrary
                              value. Low timer0 value //suggests glitch. Add this
                              to adjacent //registers to create one valid
                              //register.
      {
      do
            {
            scan_count3++;          //One glitch value already.
            FSR0 = (FSR0 + 3);      // Moves to next hi value (low //byte), 4
                                    reg. on (2 bytes per //bar value).
            value1 = INDF0;         //Value1 assigned by position.
            Convert();              //Converts two bytes to integer.
            scan_count = (scan_count - 2);      //Shifts 2 along every //cycle,
                                                so updates //accordingly.
            }
      while (value1 <= 15 && scan_count3 <= (scan_count * 2) && scan_count > 0 &&
      scan_count < 0xFD);
                              //Conditions required to confirm glitch.
..”
```

For every glitch in a waveform, there are two values either side of it, which make up the total period interrupted by the glitch. So, for a count of one glitch, there will be three consecutive data registers that together equal the correct value of that particular period. period.

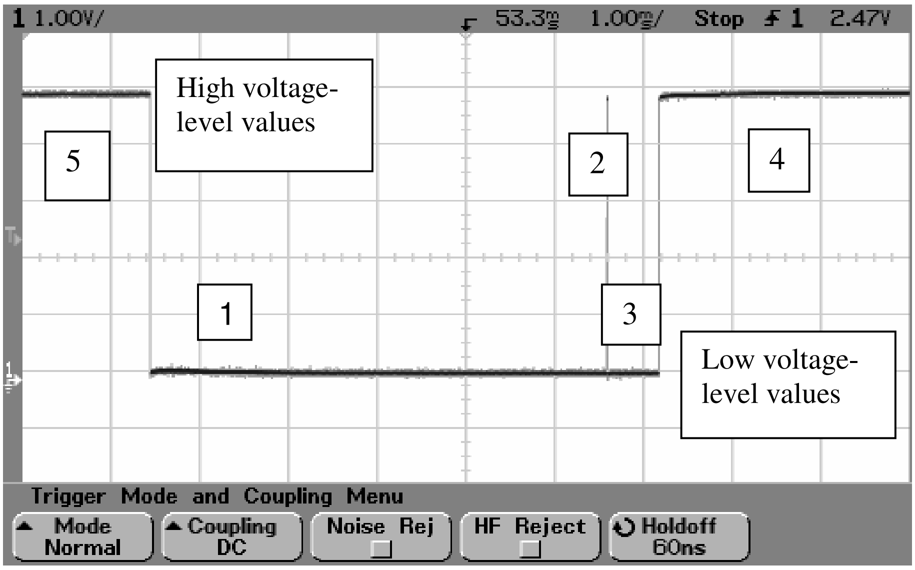


Figure . Waveform showing typical glitch in non-conductive 'low' section of scanned pattern.

For the example illustrated in , three consecutive values (boxes 1, 2 and 3) in the data set must be summed to create a single (time period) value, which represents a clean scan of a complete (non-conductive) bar in the pattern.. If the three data registers were not combined, values labelled "2" and "3" would cause a decode failure, due to their comparative values being out of proportion with that of their neighbours. This is because, after the value which defines period "5", the next (conductive bar) value is seen to be period "2". However, the value defining period "2" is obviously relatively very small, and it would thus be assessed as abnormally small and a therefore a failure of the pattern.

Every second consecutive (conductive bar) value is checked, until a relatively 'good' value ("4") is found. The difference in counts between the last known 'good' value, and the next 'good' value, is used to determine the number of adjacent bytes which need to be summed to repair the waveform period. This procedure may be called several times during the repair of a single waveform period; there is no interpretation of the barcode pattern at this stage, so the 'glitch' procedure continues until the total count of bytes in the data set has been assessed.

The code snippet underlying the description is as follows:

```
“.. scan_count3 = ((scan_count3 * 2) + 1);      //each glitch has lo //values
                                                either side.
                              //ie. 1 glitch, 3 reg.; 2 glitch, 5 reg.
scan_count4 = (scan_count3 - 1);           //No. registers actually //to be
                                           removed.
```

```
scan_count5 = (scan_count5 - scan_count4);      //Total data //registers, minus
                                                //glitches.
                              //Only updated after glitch removal.
FSR0 = (FSR0 - ((2*scan_count3)+1));      //goes to address preceding //1st
                                          glitch.
                                    //Should be a low value following //last good
                                    hi.
if (FSR0 < 0x204 && toggle2 == 0)   //Occurs when first hi value is //below
                                    threshold.
                  //Only on first iteration, because registers to be //condensed
                  into 0x204, rather than its
                  //preceding neighbour.
      FSR0 = 0x204;
else if (FSR0 < 0x205 && toggle2 == 1)
      FSR0 = 0x205;     //Must ensure return to first lo register.

value1 = INDF0;               //value1 had large value. Replace with //1st small,
                              in position indicated by //INDF0.
Convert();
FSR0++;                       //Increments position counter by one.

do
{
      value2 = INDF0;
      Convert2();
      value1 = (value1 + value2);   //adds first <=15 value to the //next..
      FSR0++;
      scan_count4--;    //Remaining data registers to be condensed.
}
while ((scan_count4 > 0) && (scan_count4 < 0xFF));

//So far, all values <= 15 have been added together; this sum should be a valid
lo register.

scan_count2 = scan_count;     //Remaining unchecked reg. updated. //Could be
                              zero.
.."
```

After each glitch cluster has been repaired, the cluster values in the sequence have been replaced with a single (two-byte) integer value. The remainder of unchecked bytes in the waveform sequence is then shifted back to fill the emptied spaces in the sequence.

The total count of values in the waveform series is updated to reflect the reduced number of bytes, and the glitch assessment is restarted from position zero. This is because the summing of adjacent bytes in the data set, within the glitch detection procedure, means that the procedure stops assessing every second byte during that subroutine. The change from alternate to adjacent-value assessment made tracking of counter positions quite difficult. That is why the procedure is restarted after every glitch repair.

5.4 Introducing the barcode pattern

The previous Paper++ project utilised an array of Manchester codes, forming a pattern space. The Manchester code consists of bars and spaces, each of the same width, arranged in a specific but unique order. The pattern is decoded by considering pairs of adjacent bars; each pair consists of a bar and space, and the order of their arrangement determines if the pair is determined to be "0" or "1". Thus, a transition from space to bar might represent a "1". The order of the alternating arrangement was determined by the time-base of the input waveform: if two bars were placed together within the order of the pattern, for example, it would represent a transition from space to bar ("1") and then from bar to space ("0"). Thus, a binary value would be interpreted from the waveform, and after checks and balances carried out, represent the value of that particular pattern.

A decision was taken by senior members of the PaperWorks project to discard the Manchester code array, and attempt a denser code structure for the next incarnation of the project. The author was not involved in the process of creating a new code structure and its array. In order to develop and demonstrate a functional conductive-pattern contact reader, a standard barcode protocol was adopted.

The barcode pattern selected was Interleaved 2 of 5; a commercially recognised standard. The name refers to the fact that two data values are encoded in the pattern, with the conductive (normally black) bars containing one value, and the non-conductive (normally white) spaces between them, the other.

Due to the effects of printing a lacquer mask to create the barcode patterns, it was found that there was a small but significant difference in bar widths, between conductive and non-conductive areas. To address this consistent 'offset' value, the conductive barcode pattern is assessed independently of the non-conductive barcode pattern. The decoded pattern is output as two bytes, each representing one value.

5.4.1 Decoding the barcode pattern

The start bars are assessed to determine the average minimum bar width. This value is used in comparison with the following bar width value, to determine its proportions. In this way, as each bar width value is compared with that preceding it, the proportions of all bars in the pattern are assessed, and the pattern value can thus be decoded. As the length of the input signal waveform is determined by a user drawing the reader across the barcode pattern, it is apparent that there can be no absolute values for the individual bar widths. Each successive bar width value is determined by the consistency of the hand swipe, and is subject to acceleration effects. This means that a set of bar width values may decrease or increase incrementally due to an accelerating swipe, even though the printed pattern was comprised of equal-width bars.

There are only two different bar widths to distinguish; the proportions being 1:3. The barcode pattern can be of any length, but is always preceded by four narrow bars of equal width – the start bars. The end of the pattern is denoted by one thick, and two thin bars. Whatever the length of the barcode, it will always contain pairs of values, so that the shortest pattern comprises two values: *e.*g. a value of "1" will decode as "01", due to there being a pair of interleaved values.

For a comparative assessment, an initial comparative value is required. This is calculated from the four start bars, as they are the minimum bar width and of equal proportions. The start bar width values are summed and averaged, to create the initial minimum bar width value against which the following bar width value will be assessed.

5.4.2 Adjustment of the data set

After the data set has been reassembled, following the noise removal procedure, and the average start bar width has been determined, the offset values due to print error distortion are adjusted. From experience, it was found that the gaps in the lacquer mask pattern were usually narrower than the bars. The adjustment procedure sought to normalise the start bar values, and so the remainder of the data set, by making the start bar values equal. It was not an arbitrary decision as to whether the narrower gap values should be increased, or the wider bar values should be decreased to compensate. As the maximum value for any one bar or gap is 255 (the value of a byte), it seemed prudent to decrease the nominally larger bar values in order to avoid a possible overflow condition. The overflow condition would exist if a large bar width value was added to, making the sum greater than

255. The result would be a (small) byte value of the difference between the summed value and 255 (: *eg*. 255 + 2 = 1, an erroneous value), effectively distorting the waveform and causing a failed read.

The larger bar width value, due to printing, does not however always correspond to the lacquer mask. Thus, the start bars are initially assessed to determine which bar width is larger, before the offset normalising procedure is performed on the relevant data set. The 'offset' value is calculated by the difference between a start bar and gap. The offset value subtracted from the larger start bit value is subtracted from every second byte in the data set, which is a simple method of normalising the data and reducing the effect of printing.

5.4.3 Deducing the pattern in the data set

Ultimately, there is only so much that can be done to restore a set of data registers to a point where it is representative of the actual pattern swiped. It must be remembered that the initial data set can be far larger, and comprised of a wide range of discontinuous values. Some automation of the restoration process must be accepted before a more sophisticated process is applied to the remaining data. The glitch routine is necessary to make basic sense of the pattern, and it is possible that the routine may alter some aspects of the data set, to its detriment.

After the average start bar width has been calculated, the next task is determining the subsequent bar width proportions. As the characters of the barcode are interleaved in pairs, each (comprising a data set of five values) is assessed independently, as it is the respective proportions of each character (data set) which are relevant. Thus, value 1 will be the decoded character defined by conductive gaps in the pattern, and value 2 will be the decoded character defined by the lacquer mask.

Initially, direct comparison is made between the start bar, and the relevant (gap or lacquer) bar following it in the pattern sequence. As the start bar width is known to be narrow, the value of the following compared bar width will determine that bar's proportion: wide or narrow. The assessment is simple, in that if two compared values are within a factor of 2 of each other, they are considered to be of equal proportion. If the compared value is within a factor of between 2 and 4 times the other, then the proportion is considered to be wide-narrow.

The basic comparison routine code is shown here:

```
“ ..if ((sample_n > (sample*0.5)) && (sample_n <= (sample*2)))
      bitset = bitset;         //Equal, whether thick or thin bar. //Bitset
                               initial value is 1.

else if ((sample_n > (sample*2)) && (sample_n <= (sample*4)))
      bitset = (bitset*3);     //Proportion 3:1; set three bits.

else
      bitset = (bitset + 3);  //8; indicating bad read.
..”
```

The evaluation becomes more complicated. Simple proportions are not enough, as comparing two consecutive wide bars will result in the same proportion as two consecutive narrow bars. Thus, a history of preceding bar width values must be carried over, so that the two compared values of equal proportions can be determined to be narrow or wide bars. This history value is also used to determine if two compared values are of proportion wide-narrow or narrow-wide.

However, directly comparing consecutive values of a barcode data set was found to be too simple, and prone to decode failures. This was because some values became distorted during the 'Glitch' procedure. It was quite easy to sport the wide and narrow bar width values in the data set by looking at them, but if the a value fell just outside the range of acceptable proportions, then the (simple) direct comparison routine would fail that character's decode sequence.

An improvement on direct comparison of consecutive bar width values was the addition of a smoothing function. As each value was assessed as narrow or wide, it would be averaged with preceding narrow or wide bar width values. Thus, rolling averages of narrow and wide bar width values were generated during the assessment of bar width proportions. The average was front-weighted as it was calculated, by combining the most recently-defined bar width value (*sample*) with the averaged value (*bitset3_ave*), resulting in an average which was influenced by the latest bar width value. The quoted code sample illustrates:

```
“.. else bitset3_ave = ((bitset3_ave + sample)/2);
      //This is a weighted average in favour of the latest //sample
      value.”
```

This function accommodated occasional outlying values by reducing their local influence on the data set, and thus the comparison routine, and improved the decoding performance of the algorithm.

5.4.4 Decoding the pattern

The result of deducing the pattern from the data set was two bytes, each representing an interleaved character in the barcode. The byte value is not important, as the position of the 1 and 0 bits represent the placement of narrow and wide bars comprising the character.

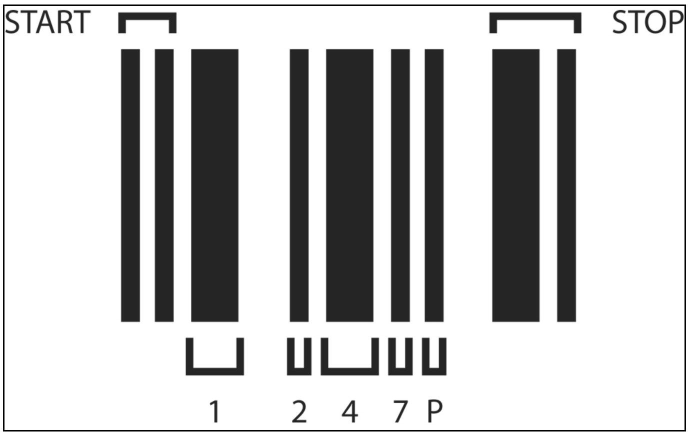


Figure 22. Logical structure of Interleaved 2 of 5 barcode format..

The format of the barcode character allows two wide bar values, and three narrow. Each bar has a representative value, in order from left to right: 1, 2, 4, 7, P, with 'P' representing parity. The position of the wide bars in the pattern serves as an enabling function; they validate the values of that position. Thus, if wide bars are in positions '1, 2', then the value of the character would be 1+2 = 3. For a character value of 1, a wide bar would be in position '1', and the second would be in position 'P'. It can be seen that character values from 1 to 9 can be represented by two wide bars, either summed, or individually plus the parity bar. The value 0 is represented by the sum of '4' and '7', which sum to an illegal (11) value, greater than 9.

The heart of the code to do this is illustrated in the following extract:

```
".. if (value3 == 0)                    //First bit test.
      code_word2 = 7;
if (value3 == 1)                        //First bit test.
            code_word2 = (code_word2 + 4);      //Second highest weighting `
                                        //factor.
if (value3 == 2)
      code_word2 = (code_word2 + 2);
if (value3 == 3)
      code_word2 = (code_word2 + 1);
follow--;
return;  "
```

Each bit in the byte *value3* corresponds to an “if” statement in the listing. The byte is thus evaluated, and the result is the value of the embedded character. Each pair of interleaved characters is processed in this manner, and the values are then set up for transmission to the interface application.

The transmission is set up as an RS-232 format, using hardwired functionality within the PIC. The data is transmitted to the USB or wireless device, which processes it automatically.

Chapter 6: Digital Pencil

6.1 The alternative nib concept

6.1.1 Introduction

Much work had been done with non-marking nibs, due to the requirement for non-intrusive augmentation. However, the very fact of integrating a digital reader with printed documents kept the option of a marking nib open. The strength of the marking concept would be its integration with conventional writing technology. This was at odds with the original aim of the investigation, which was to not compete directly with the Anoto pen application. However, the level of interest from the project partners was sufficient to motivate further research into the marking nib concept.

A simple experiment was conducted to test the theory that a metallic ballpoint pen tip could be used for a contact reading device. It was hoped that the roller-ball would reduce the sliding friction (and electrical noise) experienced with simple, formed sliding contact devices, and so increase the signal to noise ratio of the swiped barcode pattern. Two types of (black, blue and red) pen inks were selected: ballpoint and gel, which both had similar metallic ball and ball holders (the ‘nose’ of the pen, attached to the ink-filled tube). The two were chosen as it was expected that the ink, acting as lubricant for the ball, would also influence the conductive path of the signal tested.

As a comparative test, a pencil lead was included, as it was a compromise between a simple formed contact, and a lubricated roller. The lubrication for the pencil lead is due to the graphite in its core, while the graphite itself would also comprise the conductive component of the contact tip.

6.1.2 Prototypes and test method

There was no modification or omission to the electronic design of the contact reader (). The prototype used was one in which the signal conditioning was part of a separate, tethered PCB. This was purely to ease testing, as the apparatus was bulky in prototype form.

The cantilever tip design was used as support for the new nibs, with the nibs passing through a hole in the place of the original stamped dimple. Thus, the ballpoint tip replaced the simple protrusion used for contact; the reading hardware remaining otherwise unchanged. In the case of the pencil, a flexible wire connection was made between the cantilever tab and the graphite lead, with an interference fit between the lead and wooden casing.

For reliability, the second point of contact (the nib being the first) was made by fixing a wire, by crocodile clip, from the conductive paper to the reader PCB. While the reader was designed to use the electrical connection of a human user, between contact with the conductive part of the paper and the reader, the wire clip removed the variability of the user's reader-paper contact between test swipes. After all the pens and pencil were tested, the wire clip was replaced by physical contact between the tester and the paper. This was done to observe any difference in signal output, if any.

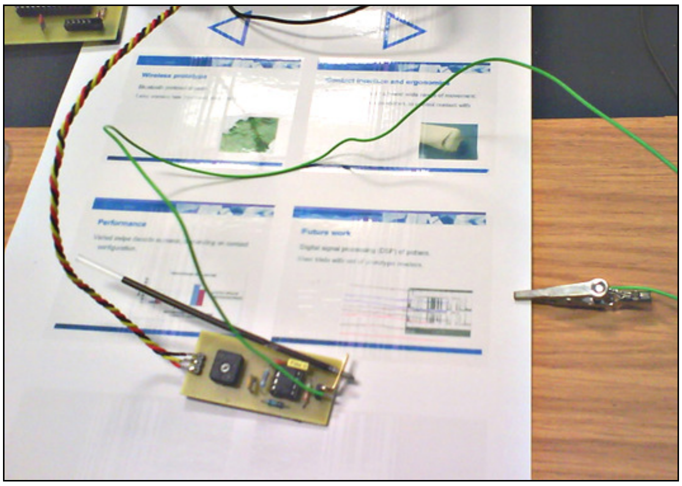


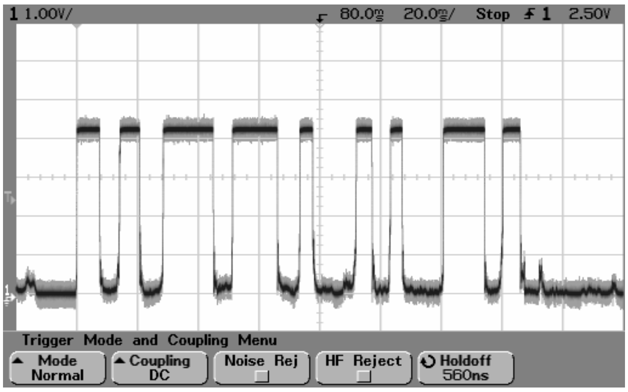
Figure . Test setup, showing ballpoint pen ink tube and tip, mounted in signal conditioning PCB.

Each ink and tip was tested on a separate barcode pattern, to avoid contamination of results. Each swipe was made over a previously unmarked part of the pattern, but only one pattern was used per ink. So, for the two ballpoint ink types, and the pencil, three separate patterns were used. Each pattern was swiped 10 times: enough to determine a trend.

The output signal from the reader signal PCB was connected to a digital storage oscilloscope (Agilent 54621A), so that the image of the scanned waveform of each pattern could be saved. The swiped barcode pattern was not decoded in the tests; just the quality of the waveform was assessed visually. Thus, the results were not quantified specifically.

6.1.3 Results

The signal to noise ratio of the ballpoint pens (non-gel) was relatively high, and the swiped pattern could be discerned easily. This phenomenon was repeatable, even after multiple sweeps on the same path. The pen did not mark the lacquer significantly before the first gap was encountered; after that, the ball began to roll and lines of ink were deposited on all portions of the pattern.



Mode Normal
Coupling DC
Holdoff 560ns

Figure 23. Ballpoint pen tip. Indicative of performance.

The gel ballpoint pens did not yield a good result. The signal to noise ratio was relatively low, and the swiped pattern was not clearly discernible. There was initial marking on the lacquer at the beginning of the swipe, and ink was deposited mainly on the unmasked paper portion of the barcode patterns.

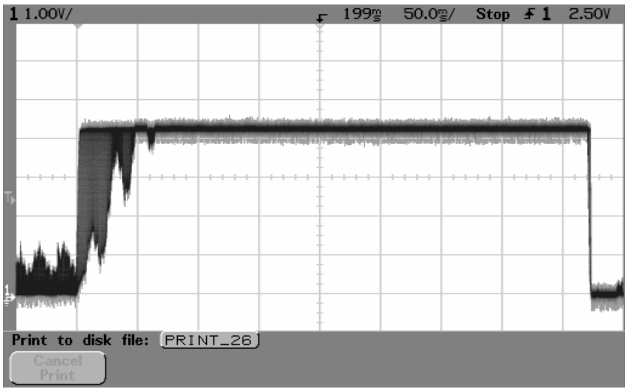


Figure 24. Gel ballpoint pen. Pattern largely non-existent. Indicative of performance.

The pencil did not mark the lacquer, but marked the uncoated portions of the barcode pattern. The signal to noise ratio was relatively good, but not as good as that of the ballpoint pen (non-gel). The pencil yielded significantly better results that that of the gel ballpoint tip.

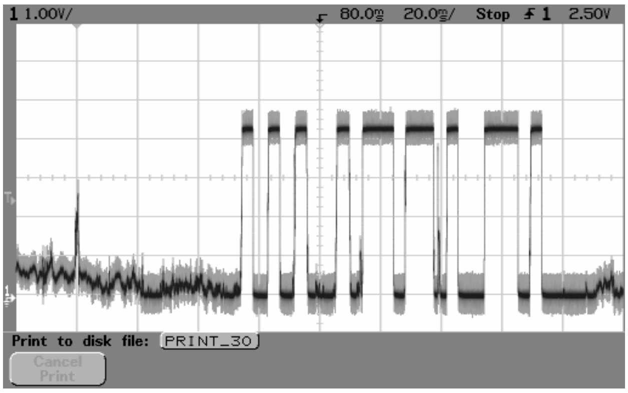


Figure 25. Pencil (graphite) tip. Indicative of performance.

6.1.4 Conclusions

In essence, the ballpoint pens proved to be quite successful. The gel pens, while also using the ballpoint mechanism, appeared to create a conductive path over the lacquer, as well as on the conductive coating of the paper. The reasons for this are not clear, but one theory is that the solvent in the gel ink destroyed the insulation of the lacquer printing. The pencil worked quite well, but lacks the constant radius of the ballpoint, and thus possibly, its long-term reliability.

While there was a clear distinction in performance between the two types of ink, there was little distinction evident amongst the different colour inks in the two groups. The main issue with these tips is that they use ink as a lubricant. Further tests would be required to determine if a) the ballpoint tip can function without ink/lubricant, and b) if a clear ink/lubricant could be found which would perform as well as the standard ink. The sliding friction was very low, and felt much better than the dimpled cantilever in use. This may have some effect on the user experience, if less swiping effort is experienced.

6.2 'Digital' pencil design and development

The pencil concept resulted in requests to produce a proof-of-concept model. Although this was, strictly, outside the work package remit, it was considered a worthwhile endeavour. As the functional aspects were so similar, the major effort was in packaging the components (PCB, battery, and pencil) as neatly as possible. It must be acknowledged that the PCB was still much larger than would be expected of a commercially developed product.

A further, modest volume reduction was realised by replacing the originally selected rechargeable 3.6V CR2 lithium battery with a 6V non-rechargeable 4LR44/PX28L battery. The difference in length and diameter was about 2mm less. The voltage difference was accommodated by the power management circuitry already present.

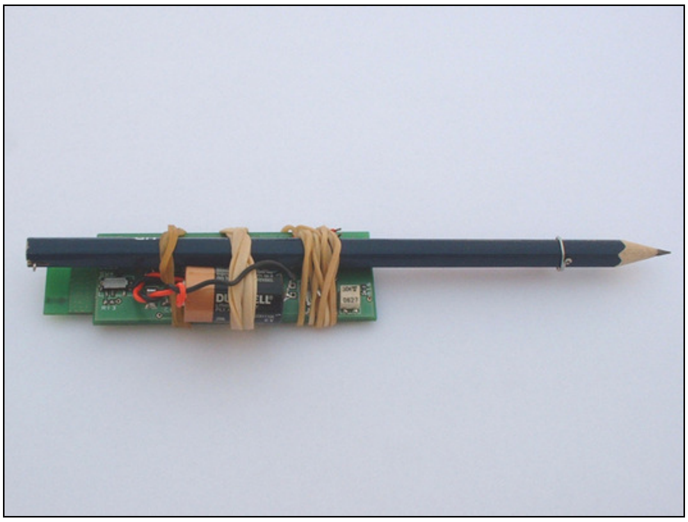


Figure .28 Original wireless pencil prototype, using earlier 2nd-year PCB.

Several key design issues were considered during the modelling stage. Firstly, the pencil was removable; provision had to be made to attach and release it. Secondly, the contact tip and external (hand) contact were part of the same pencil; this implied that temporary but reliable electrical contact had to be made between those parts of the pencil and the electronics within the casing. Thirdly, the pencil had to have a coating or similarly thin sleeve, which was electrically conductive in contact with the user's hand.

6.2.1 Pencil attachment and release

It was decided to insert the pencil into the device, rather than clamping it. This would protect all internal components by removing them from sight and reach. Clamping would require moving parts, which added to the complexity, so this was further reason to reject it as a concept. The insertion of the pencil also promised a positive guiding and location mechanism; once the pencil was fully inserted, it would be fully constrained.

Once the pencil was inserted into the device, it had to be secured to it. Movement of the pencil would cause intermittent electrical contact problems, which was not acceptable. To improve the reliability of the contacts, a barb design was conceived. With the pencil inserted, spring pressure would bear on its tip, and tend to push it out of the device. The proposed solution was to have a little plate 'barb' which would allow the pencil to slide past on insertion, but 'self apply' if the pencil moved in the opposite direction. The angle of the barb was determined by simple prototypes. Removal of the pencil was facilitated by a moulded cantilever, which could be pushed against the barb by a finger, and so push the barb off the side of the pencil. The fixing mechanism is not considered very strong, as the spring force of the rear contact is not great.

6.2.2 Pencil electrical contacts

Contact had to be made with the pencil lead. Originally, a sharp metallic tip was considered, to make contact with the flat rear end of the pencil. After deliberation, the reverse was decided: the rear end of the pencil would be sharpened, and that end would make contact with a concave connector. The advantage of the second configuration was that the point would 'auto' locate with the concave connector, and reduce the precision of fit required. Even if the lead was blunted, the fact that it had to make contact with a larger metallic connecter gave greater assurance of positive electrical contact.

There was also the concern that a sharp-pointed connector could damage (or miss entirely) the lead of a flat-ended pencil, and result in poor electrical contact.

A simple cantilever sliding contact was designed for the (coated) side of the pencil (). It was hoped that the securing barb could be pressed into electrical service, but as the prototype was so new, the safer option of separate components was chosen.

The discrete on-off switch of the original schematic design was discarded in favour of a bespoke one, built into the casing. The idea was to switch the device on and off with the insertion and removal of the pencil. To that end, two cantilever contacts were stacked together alongside the pencil tube in the device; the insertion of the pencil would press them together, and act as a component of the switch.

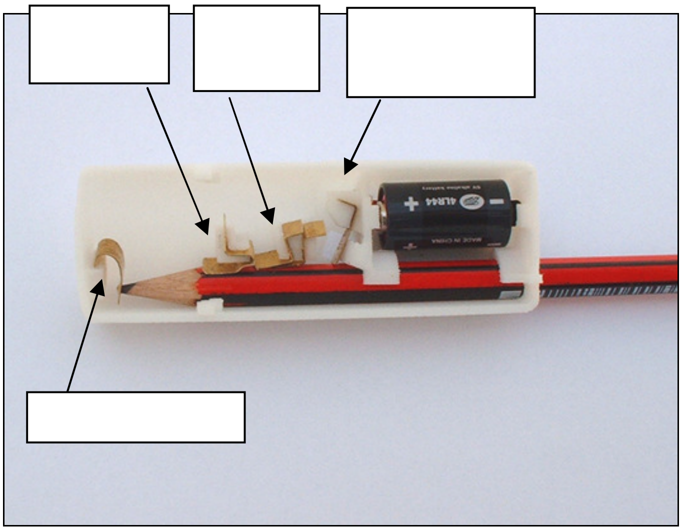


Figure . Internal structure of wireless pencil module, showing the necessary contacts.

The switch component which contacted the external foil strip was un-insulated. There was the danger of a short-circuit condition existing between the unregulated battery voltage on the switch component, and the regulated voltage on the (pencil) end contact. A solution to this was to insulate the switch contact area on the pencil end with adhesive tape, without breaking the foil contact strip between each end of the pencil ().

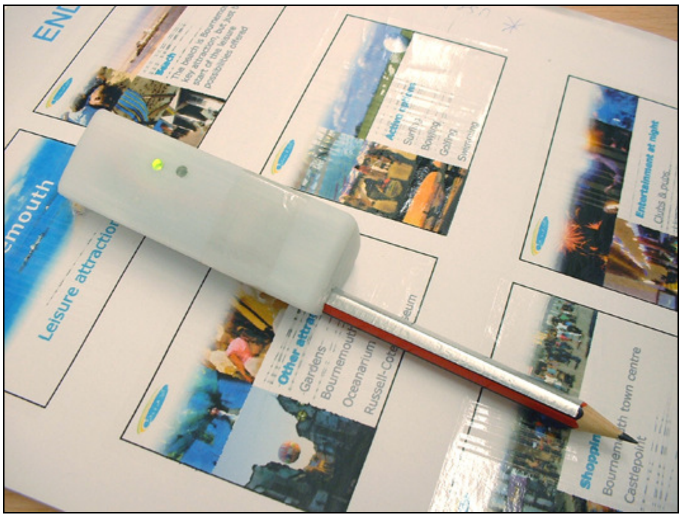


Figure .30 Wireless pencil module shown activated, with external foil contact strip on pencil.

6.2.3 Pencil user trial

A number of experiments were carried out in order to test the performance and reliability of the contact barcode reader. In total, nine participants assisted in the study. The participants had no prior knowledge of the functionality and usability of the reader. Each participant was asked to swipe the reader twenty consecutive times across a conductive pattern, part of the PaperPoint slide handout print.

The print sample was a complete inkjet-printed graphic and lacquer pattern construction, and thus representative of the print quality required for the project. The print sample was used at ambient conditions, and had not been humidified to 80% RH as with previous user studies.

Results from the reader were recorded individually after each swipe. The data from the reader was sent to the computer wirelessly via the Bluetooth module integrated in the reader. The application logging the results was written in Visual Basic 6, and saved each user set as a text file. The results are presented as stacked bars, representing four levels of swipe decode success.

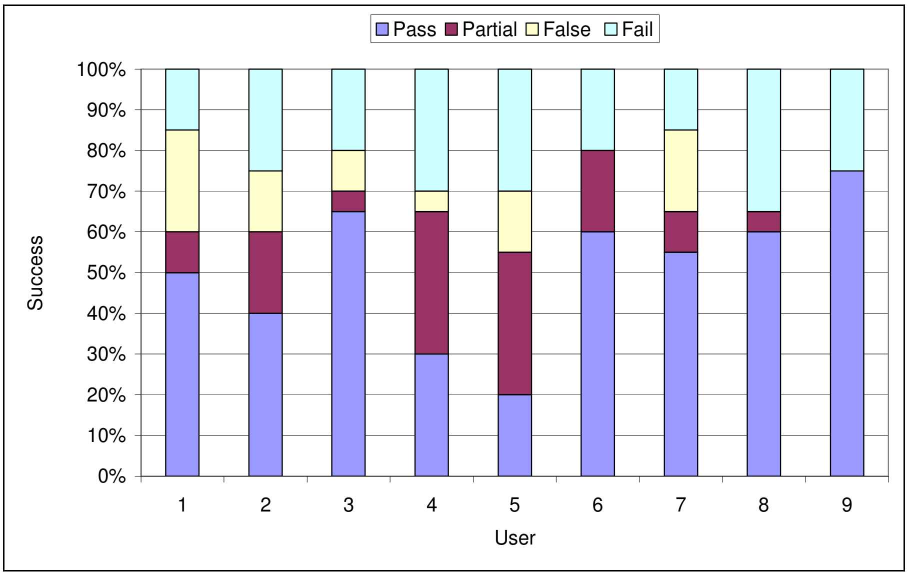


Figure .31 Results graph from 9 users; 20 consecutive swipes each.

The same test set, using fresh print samples, was done using the conventional, third-iteration reader. There, the rate of successfully decoded 'PASS' swipes was just over 1%. What the results indicate, is that the pencil reader is superior (just over 50% 'PASS' decode success) to the brass-tipped reader of the same electronic configuration. The core difference lies with the tip materials; the (HB) graphite blend is softer than brass. The roughness of the un-lacquered areas of the coated paper provides a key for the graphite, whereas there is little observable graphite laid down over the smoother lacquered areas of the printed barcode patterns. However, as the graphite tip appears to conform to the paper surface, it results in a more consistent sliding contact, and so a more consistent generated waveform signal, with less noise. This is the main factor, which is attributed to the performance of the pencil reader.

Beach

The beach is Bournemouth's key attraction, but just the start of the leisure possibilities offered

Figure .32 Print sample, showing graphite tracks keyed to non-lacquered areas of the pattern.

Chapter 7: System evaluation through user trials

Over the course of research, several user trials were carried out to test a particular developmental stage of the reader., the majority of which were carried out by the author. Most of these tests were informal and conducted by the author, the main objective being to discover if the devices were usable by people unfamiliar with them. The two “comprehensive” user trials were set up formally, and conducted by colleagues of the author.

7.1 Initial user study: tethered reader

7.1.1 Method

A simple test was devised and conducted by the author, using code samples which consisted of two two-character test patterns, masked with clear lacquer. The two characters were presented in the middle of a sheet of A4 paper, and outlined to make their position obvious.

The barcode reader used was the USB tethered device, developed for the first year of the EU project, with a concentric tip arrangement. Changes made were an update to the firmware in the device, which corrected a fault with the LED indicators (a coding error caused the incorrect LED to flash, although the transmitted data was not affected), and removal of some redundancy in the code. The device was considered to be functionally the same.

For comparative purposes, the output from the device was processed in a simple Visual Basic application, which logged the scan results (Pass = 1, Partial = 2 and Fail = 0) and saved the data to a text file. Thus, any number of scan results could be collated in a spreadsheet to serve as part analysis of the test. A series of 10 consecutive swipes was allowed per stage, per user.

The test was divided into two stages. The first introduced users to the pen, and only a basic explanation of its operation was offered. This described the device as a “contact barcode reader”, and the user was asked to “draw a line through the pattern”, swiping the barcode in a manner that seemed appropriate to them. A parallel was drawn with the common ballpoint pen, to guide the use in terms of handling and pressure of stroke. No feedback was given to the user during this part. The first of the two patterns was used in this stage.

The second evaluation stage offered more to the user, as the device was rotated to reveal the indicator light on the body. The role of this was briefly explained to the user, in that the colour of the LED indicated a good scan (green flash), partially successful (amber) or a fail (red). The user was advised to use the LED indication to modify their use of the device, in an effort to improve the performance from the two (user and device). A hint was made about varying the speed of the swipe in order to find the range of best success. Other factors such as angle of device to paper, lead and lag, were omitted from the explanation. The second pattern was used in this stage, to assure comparable media quality.

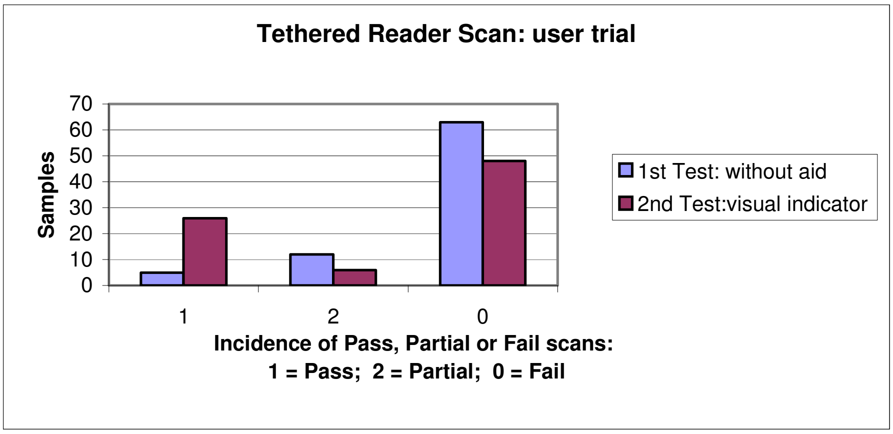
The reason for effectively limiting the success of the trial was to determine several things:

- allowing the user to (briefly) familiarise themselves with the device and the printed paper sample;
- the rate of successful scans during this first stage, based on the user's intuitive handling of the device;
- if the LED visual indicator was considered useful as feedback;
- if the LED indicator had any positive influence on scans, based on the user's response to it;
- if there was a significant difference between the first unschooled scans, and those from the second, (limited) informed scans.

7.1.2 Results and Discussion

The outcome of this series of tests were divided into two sections: qualitative and quantitative. Based on observations only, the first stage of the test appeared to be tedious and without merit from the immediate feedback returned. It was difficult not to offer assistance to each user, and so the swipes were completed quite swiftly. Another reason for this first stage was to limit the introduction to the user, as mention or disclosure of the indicator light was considered a spoiling factor (based on the premise that the temptation to see the scan result would affect the nature of the test stage).

The second test stage was expected to create awareness in the user about the direct results obtained from the device. Thus, it was hoped that the user would attempt to learn how best to manipulate the device in order to achieve good scans. Perhaps the set of ten swipes allowed was too few for this stage to be successful. What was evident is that the indicator light created some confusion. The user, when faced with a (failed scan) flashing red light, was unsure how to alter their technique to achieve a better result. Similarly with the green light, as the user was unsure how success had been achieved. The problem was that the difference in technique between a failed and a successful scan is subtle. Two users (F, H) did not appear to understand how to modify their technique, to the extent that their results were consistent (failed scans); no obvious change in swipe speed was observed despite encouragement to do so. One user (A) had good results in the first stage, and understood how to maintain that result in the second stage.



.Figure 33 Tethered reader user trial results.

Overall, an overall improvement in successful scans was recorded (): 32.5% (26/80), compared to 6.3% (5/80) in the first stage. If the partial-success results are included (bearing in mind that a partial scan is where either the stop-bit of the code was not recognised, or one of the two characters failed to decode), then the mixed-success rate increased from 21.3% (17/80) to 40% (32/80).

The higher incidence of successful scans in the second stage points to the deliberate effort of users to achieve a consistent swipe. The drop in partial-success results reinforces this result, but the overall performance is still far below expectations.

7.1.3 Conclusions

The tethered barcode reader was not an easily usable device, and required training for any reasonable result to be achieved. While some training in use may be considered a reasonable requirement, the nature of the application suggested that the current solution was unworkable. For this device to be considered a worthwhile instrument, it must be capable of delivering positive results at a significantly higher rate, and within a short time-frame. For that to be effected, further work was required on the algorithm of the internal firmware of the device.

Observations of the users during the test show that their expectations were not met; the concept of a barcode scanner as an accurate device, incorporating mature technology, did not match the results obtained.

7.2 First user trial with wireless reader

7.2.1 Method

The purpose of this study, conducted by the author, was to test the first fully-integrated package of new reader electronics and casing, and to measure its success in decoding the latest printed samples for the project. It was not intended as a comprehensive investigation, but to highlight any obvious faults with the system. It was hoped that users would enjoy greater success in swiping with this design, as compared to the previous study, using the pen-like tethered reader.

Six people took part in the exercise, using a single sheet of paper. The paper had ten unique barcodes screen-printed on it, over inkjet-printed artwork. The paper represented a six-slide handout for a Power Point presentation. Additional barcode patterns were printed at top and bottom of the handout, for navigation purposes in the Power Point application. In total, there were ten unique patterns on the page.

The subjects had the basics of operation explained to them: the fact that the reader had to maintain contact with the paper, the action of swiping to read the barcode, the necessity of maintaining physical contact with the non-lacquered areas of the paper (with the free hand), and the need to remain within the bounds of the lacquer-printed area surrounding each code.

Each barcode pattern on the paper was swiped once, and then the process repeated, to yield twenty results per subject. Thus, the test was not a repeatability study for a single code pattern, but a reliability study using a variety of code patterns.

7.2.2 Results

The results were separated into “pass”, “fail” and “partial success” values. Although there was no further processing of the partially decoded output values, these were recorded as an indication of the decoding process. Pass values were recorded as “1”, partial as “0.5” and failed as “0”. The reason for the values was to differentiate the various results within the same data file.

The best set of results had 50% successful decodes; the lowest, 30%. The highest failure rate was at 45%, the lowest, 10%. This test yielded a total pass rate (encompassing all users' results) of 40.8%. Including partial results (of which some were valid decoded values, but with error code attached due to failed decoding of stop bits), this test yielded 75.9%.

7.2.3 Conclusions

This second informal user trial was more successful than the first. Changes to firmware in the reader, and to the physical interface, had made significant improvements. While the users’ success with the reader was not runaway, the pass rate was doubled. That is considered reasonable, given that the users were not familiar with the reader.

7.3 First comprehensive user trial with integrated application

The preliminary tests of the wireless reader had proved its basic functionality. The next requirement was to test that functionality more comprehensively. A project partner (ETH Zurich) had developed an interface application, which would allow a device like the reader to interface with a Microsoft application, PowerPoint. The test was devised and conducted by a colleague at Brunel University.

Eight users were involved with the test [1], over a period of two days. The swipe success results were widely variable, from 0% to 96% amongst the users. The test was not considered a success, as too many factors were not controlled. The lack of fresh prints and the variation in environmental conditions created many problems. The results triggered an investigation into the environmental sensitivity of the printed samples (see section 7.4 below).

What the study did demonstratedemonstrate was that while the system was unreliable, the reader was capable of functioning quite well in the right hands. The fact that it also yielded a 0% result indicated that it was not yet robust enough, and this spurred the redesign of the reader itself.

The full study is included in Appendix 1.

7.4 Environmental testing of printed media

Due to issues with variable swipe success, the author decided to conduct a test of the effect of humidity on the success of swiping. The two types of sample were the standard lacquer-printed barcodes on conductive-coated paper, and the lacquer-printed barcodes printed over an inkjet graphic layer on conductive-coated paper.

The conditions of humidity were extremes: 80% relative humidity (RH) and 20% RH, at 23 °C. This corresponds with an earlier test conducted in 2005, on the original coated paper. A control was a set of equivalent paper samples, left outside the humidity chamber.

7.4.1 Test conditions and method

The test equipment used was a Rotronics Hygrogen temperature and humidity generator, Rotronic humidity and temperature meter, Wolfgang Warmbler SRM-110 sheet resistivity meter, and the PaperWorks wireless reader.

The methodology of testing was to measure the sheet resistivity of the sample, then swipe a barcode a number of times (40) in order to generate swipe success data. To remove any effect of the operator on the test, the contact band of the reader (normally in contact with the operator) was directly tethered to the paper's (conductive) surface by crocodile clips.

The control samples were measured at an ambient temperature of 25.6 °C and 41% RH. The temperature in the humidity generator chamber was set to 23 °C.

7.4.2 Results and discussion

The results from the test are shown in Table 2 show the difference in performance between plain and graphically-enhanced conductive patterns. The plain "Blank" patterns were examples of the lacquer mask printed over. 'Blank' refers to the barcode sample without any inkjet graphics printed on it. 'Inkjet Print' refers to the conductive sheet. The graphically-enhanced "Inkjet Print" samples had a full-colour (CMYK) image printed on barcode sample where the graphics were printed on the (A4-sized) conductive sheet sample first, before the lacquerinsulating mask was applied. The test was to determine the effect of the printed ink on the conductive quality of the paper.to create the barcodes. The barcode patterns were the same, in each case.

The sheet resistivity was measured for the control samples, and at the two extremes of humidity. The control sheet resistivity was 10^7 Ω/□. At 20% RH, the resistivity returned to 10^7 Ω/□.

Table 3. Swipe decode results: printed and non-printed masked barcodes.

	Swipe success (%)					
	Inkjet Print @ 20% RH	*Blank @ 20% RH*	**Inkjet Print control @ 40% RH**	*Blank control @ 40% RH*	**Inkjet Print @ 80% RH**	*Blank @ 80% RH*
Pass	**0**	*0*	**0**	*20*	**77.5**	*40*
Partial	**0**	*20*	**7.5**	*12.5*	**10**	*22.5*
False	**5**	*25*	**32.5**	*25*	**10**	*10*
Fail	**95**	*55*	**60**	*42.5*	**2.5**	*27.5*

Table 4. Success rate of decoded swipes, on plain and graphically-enhanced patterns.

The sheet resistivity was measured for the control samples, and at the two extremes of humidity. The control sheet resistivity was 10^7 Ω/□. At 20% RH, the resistivity returned to 10^7 Ω/□.

7.4.3 Conclusions

The effect of humidity on the paper was marked at the 80% level of relative humidity. There was less difference in results between the control and the low-humidity samples. This does point to the conductivity of the coated paper being the most significant component of the system, in terms of swipe success. Previous user trials did not take note of the ambient conditions, so it is difficult to directly corroborate their results with the paper quality.

It is possible to increase the gain of the amplifier section of the reader, to compensate for increases in sheet resistivity. However, an increase in gain amplifies not just the barcode pattern, but also all the noise around it. This has created difficulties in extracting the relevant pattern from the large quantity of swipe data, and is thus not a simple solution.

It also appears that the inkjet layer has an effect on the swipe success. At lower levels of humidity, the blank prints (no graphic layer) yielded slightly better results. The results were transposed at the higher level of humidity, which suggests that the inkjet layer was predominant in this result.

The higher success of the high-humidity inkjet print samples suggests that the ink layer retains a lot more water than any other part of the paper when exposed to high humidity. The blank samples do show that the other parts of the paper retain water to aid conductivity, but not to the same degree. At low humidity when there is not much water to be retained the ink layer appears to be more of a hindrance than help by adding a slightly insulating layer to the paper.

7.55 Second comprehensive user trial with integrated application

In collaboration with Kings College London (KCL), a test of the wireless reader and its system of application was conducted to determine its effectiveness, qualitatively. The trial was prepared and managed by Dr Karola Pitsch, a researcher at KCL, and project partner.

Changes to the print media were that it was exposed to humidity in an environmental chamber, to elevate its moisture content to a nominal 80% RH. The printed patterns and content were unchanged from the first comprehensive user trial. Enough fresh printed sheets were prepared to allow a new sample for each user, which avoided any issues with wear and tear. The tests were conducted over a period of three days, in a climate-controlled environment.

The test did not concentrate purely on reader decode success, but was more focused on the qualitative experience. All three reader case styles were trialled, and the user responses were considered most important. The main aim of the trial was to have the users give a slide presentation, using the reader as slide sorting device. The application driving the presentation was written by the project team at ETH Zurich. The application linked the output from the reader to commands used to control the presentation, such as '*Next*', '*End*", '*Slide No. xxx* ', etc.

The users were introduced to the devices without any explanation of the devices' method of use,, but all groups managed to use the reader, some with limited success. Two groups managed to complete the presentation. All groups initially attempted to use the reader as a pointing device. Attempts to stamp or tap the reader on the paper elicited no response, after which swipes were attempted.

What was interesting is that even though most people appeared familiar with barcodes as a technology, most had experienced it by observation of laser barcode scanners in a retail environment, i.e. they had no experience of using a contact barcode reader. Thus, the physical action of swiping the barcode was novel, and the fact of its (printed) near invisibility was frustrating. As the barcodes were presented as having the functionality of buttons, locating them correctly became more important.

7.5.1 Conclusions

It was observed that some frustration was caused by the delay between a swipe and the output on the monitor. The reader did not meet the initial expectations of the users, and some were disappointed that it only decoded the barcodes in one swipe direction. The second reader casing (wedge) style caused the greatest confusion, as it led users to mistakenly use the wrong (wedge) end of the device. Users also attempted to depress the contact tip, mistaking it for a button. This may have been because they had been told that the device was wireless-enabled. Ultimately, the general consensus was that the device was novel, but its limitations (in the context of its application) made it unattractive as a prospective complementary technology.

Chapter 8: Conclusions

The goal of this work was to produce a cheap, low-cost reader capable of reliably decoding conductive patterns printed invisibly on paper, and relate that information to a location in an area defined in the digital domain. With regard to the stated objectives setof this investigation, as laid out in Chapter 1, it is concluded that all have been met, with some limitations. The current state of the introduction, most were achieved. Model constructionart was enhancedreviewed, and expedited byserved as context for the use of a rapid prototyping machine, and external facilities chosen to optimise and fabricate surface-mount PCBs. The wireless prototype reader proved the most successful. The reliability of the combined user, reader, and paper system is still variable, driven largely by user factors and variation in the conductivity of the paper with humidity. However significant improvements have been made in that the Brunel reader can operate with very low visibility patterns. subsequent research. Functional hardware and software prototypes were designed and built, and synthesized into usable tools. Specific points have been noted in section 8.1 and 8.3. The characterisation of the system was limited, but investigated sufficiently to define areas of strength and weakness; elaborated further in section 8.2.

The final objective, of identifying areas of further work, was not explicitly visited. However, it is acknowledged that significant work is required on the processing algorithm, and the digital pattern itself. The barcodes used were ultimately limited, in that they did not improve on the Manchester coding of the the preceding project. That development was beyond the scope of this work. Thus, the development of the hardware was the major contribution to the project.

8.1 Scanning and algorithm

The reliability of decoding was variable, as so many factors came into play: user interaction, electrical contact, conductivity of the coated paper and its sensitivity to humidity, and the decoding algorithm itself. The influence of user interaction was partly solved by design, in developing a physical interface which forced correct handling of the device. The electrical conduction of signals through the user, paper and device could not be fully controlled, but was consistent enough to suggest its validity as a component of the system. Further work on optimising the transmission of the signal over the skin is considered one of the areas worth investigating.

The decoding algorithm worked surprisingly well in optimal conditions, given that it utilised no digital signal processing or mathematically complex filtering mechanisms. The very simplicity of the algorithm made it vulnerable to poor pattern signals, in anything less than optimal conditions, as it did not employ pattern recognition or fuzzy logic. Certainly, more sophisticated algorithms would have greatly improved the decoding success of the device. The earlier Paper++ project used a more comprehensive pattern, which went further towards building a true digital paper space, but with the focus on hardware development, this project did not build on that solution.

8.2 Printed media

The environmental sensitivity of the coated paper was not resolved, only investigated by the author (see section 7.4). The paper, coating, and printing were largely beyond the control of the author, although much work was carried out to understand and attempt to improve the medium. In this regard, the system was not fully characterised, as set out in the introduction. If the substrate was more conductive, in the hundreds of Ohms resistivity rather than millions of Ohms measured on the current paper, it is believed that the system would have been more robust. The final printed samples were not representative of the ideal construction, due to difficulties with the printing process.

8.3 Digital pencil

The digital pencil was a surprise success, as it was far better in decoding than the metallic-tipped reader. The pencil's graphite tip made better contact with the printed paper, and was also less sensitive to the environmental effects on the paper. ManyM users were able to achieve repeatable, successful swipes with it. The digital pencil was considered a positive outcome for the hardware component of the project. As a side-bar to the planned wireless model, it managed to encapsulate the best aspects of the hardware endeavour.

8.4 Commercial viability

The low-cost aspect of the project was a relative expectation, with respect to the cost of the Anoto pen. As the Anoto pen retailed at around £100 or more (at the time of writing), dependent on manufacturer and functionality, the cost of the simpler reader would be considerably lower. No calculations were made on volume costs for a mass-produced wireless reader, and the cost of licensing (application software) was not investigated. However, Bluetooth-enabled headsets for mobile phones could be purchased from £5 off the Internet at the time of writing; the reader is a simple device which incorporates comparable technologies, so could potentially fall into a similar price range. Volume production would likely be far lower though, which would affect costing considerably.

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Appendix 1

User Study 1.

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

Katy Jenkins
Dt04krj@brunel.ac.uk

Julian Wood
Julian.Wood@brunel.ac.uk

Darren Southee
Darren.Southee@brunel.ac.uk
+44 (0)1895 266323

Prof David Harrison
David.Harrison@brunel.ac.uk
+44 (0)1895 266321

Prof Neville Stanton
Neville.Stanton@brunel.ac.uk
+44 (0)1895 265543

School of Engineering and Design
Brunel University
Uxbridge, Middlesex, UB8 3PH
UK

ABSTRACT

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

General Terms

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

Keywords

Digitally Augmented Paper, Wireless Pattern Reader.

INTRODUCTION

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

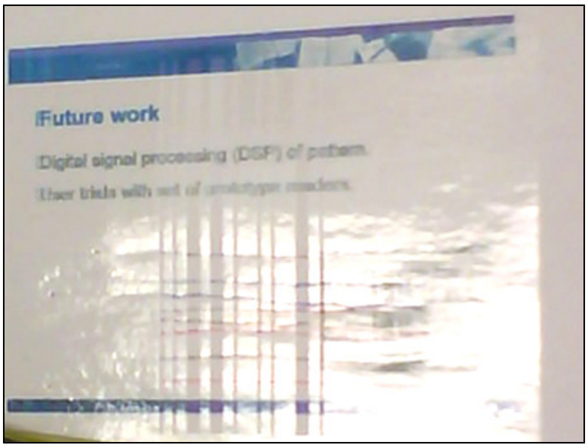
A review of previous work in developing relationships between digital content and paper can be found in 'The Disappearing Computer' [3].

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

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

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

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



Future work

Digital signal processing (DSP) of pattern

User trials with set of prototype readers

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

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

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

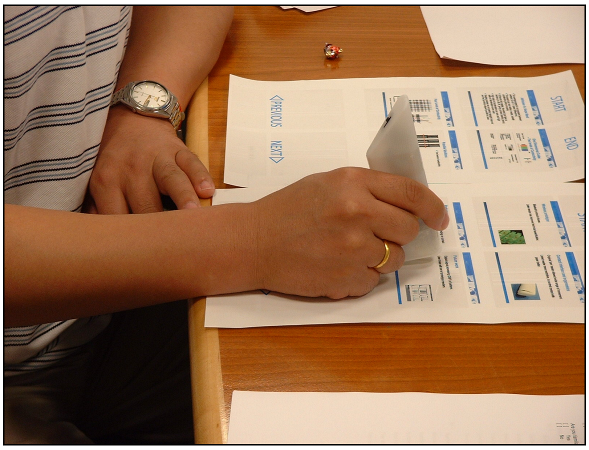


Figure 2. Pattern reader used on PaperPoint printout.

SUMMARY

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

DESCRIPTION OF THE TEST

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

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

Apparatus

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

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

Procedure

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

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

Task

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

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

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

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

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

Aims

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

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

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

RESULTS

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

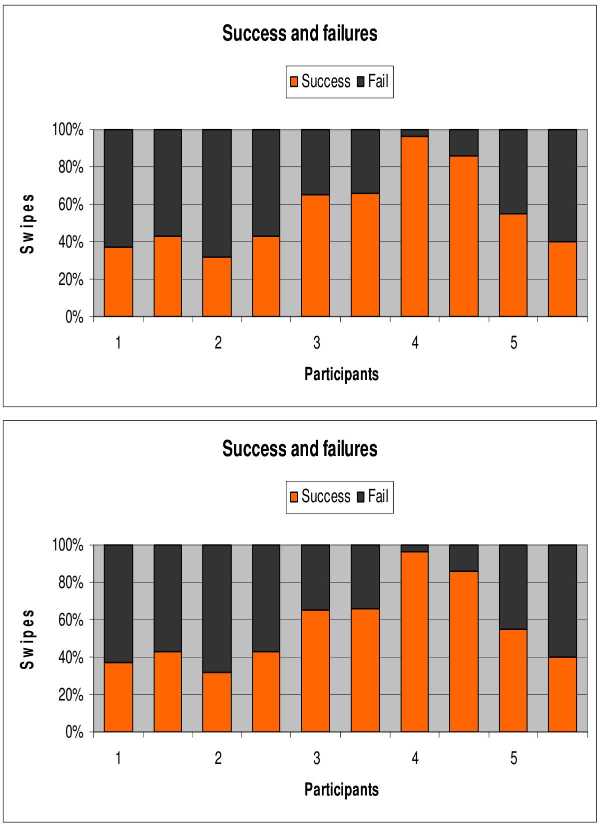


Figure 3. Percentage of successful results on 1st day.

Figure 4. Percentage of successful results on 2nd day.

4.1 Intuition

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

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

Effectiveness

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

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

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

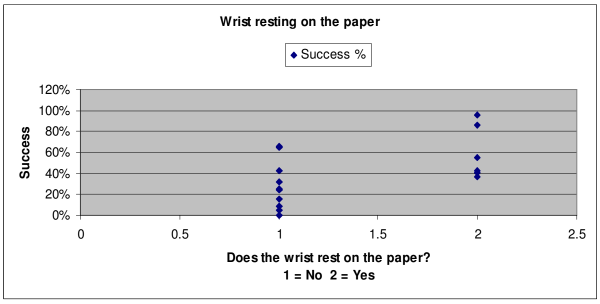
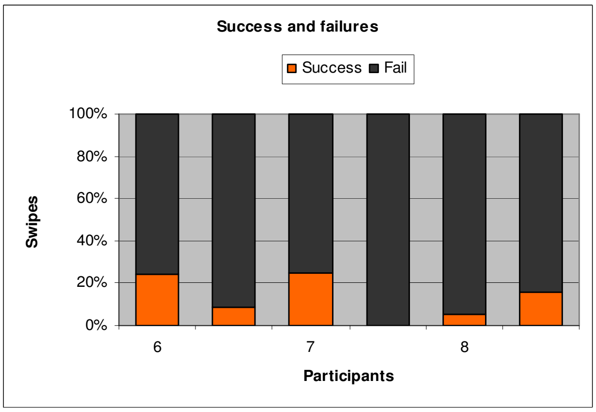


Figure 5. Wrist resting on the paper compared to success.

The previous graph shows that there is an apparent correlation between the participant's wrist resting on the paper and the success rate. There is greater success when the wrist rests on



the paper, implying that the user has more control over the consistency of the swipes. Further testing would be needed to verify whether this is the case, or whether the correlation is due to natural variability.

Efficiency

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

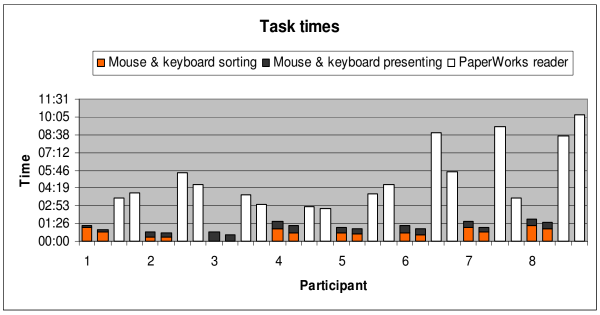


Figure 6. Task times for control and reader.

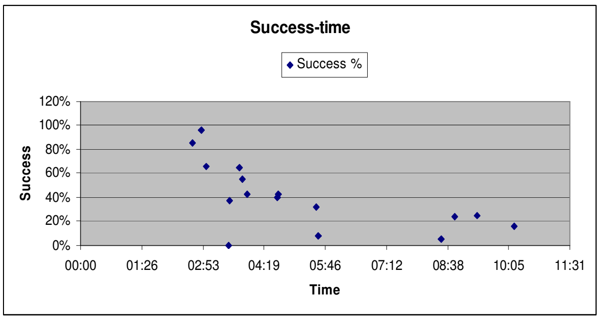


Figure 7. Time taken compared to success.

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

Learnability

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

Comfort and health

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

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

Satisfaction

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

CONCLUSION

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

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

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