Magic Bookmark: A Nonintrusive Electronic System for Functionalizing Physical Books

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The use of physical paper is often preferred due to its unique physical properties that improve various aspects of reading. However, digital media and information are more engaging, diverse, and up to date, thereby challenging the existence of paper in our everyday life. By combining the two types of media in a seamless way, the interactivity of multimedia content can complement the reading experience, maintaining the unique feel of paper books. The current state of the art addressing this application negatively impacts the reading experience and often does not consider the manufacturability and sustainability of the proposed solutions. Herein, the Magic Bookmark, a technical solution for automatically recognizing the open page of a physical book, to provide seamless augmentation without changing the user's behavior and experience significantly is introduced. Three alternative solutions are implemented, with various degrees of ease of use, manufacturability at scale, and reliability of data reading. The optimal realization is found to be a reflective optical readout array, for which routes to implementation that may allow blending the graphical and functional aspects of the augmented book are proposed.

1. Introduction

1.1. The Future of Paper

Paper's unique physical feel improves various aspects of reading against the equivalent digital experience. For example, reading printed content on paper offers better comprehension, improves browsing and bookmarking, allows for free-form annotations, and improves collaboration.[1–5] Research also suggests that the better positional indexing and improved reading experience of paper-based books improves memory and recollection of information.[6] This has also been linked to the use of physical paper for training from a young age, which is the default media in schools.[7] In addition, the visual fatigue caused by screen-based electronic devices often drives people to the use of paper for longer reading sessions.[7]

However, the value of paper and printed information is challenged by the rich features offered by digital media. Screen-based devices, which are used to consume rich digital content, provide attractive alternatives to paper-based information.[8]

These solutions (tablets, e-readers, etc.) offer internet access, simplify content sharing, and allow for effortless collaborative annotation. Additionally, electronic devices can store a large library of books and publications in a small form-factor device, which can be carried by users with ease.

These features challenge the existence of printed information, despite the unique qualities of paper that cannot be replaced by digital media. An effective solution, which utilizes the best of both worlds, may be advantageous, and the coexistence of the two types of content needs to persist.[9]

1.2. Prior Work

In this work, we are progressing our investigation into augmented paper books.[10] In our previous work,[10,11] an ecosystem for smart paper objects, named “Next Generation Paper (NGP),” has been proposed, including an authoring tool for generating and linking digital and physical media, a proprietary application for content consumption, and two classes of technical solutions to seamlessly recognize the open page, without affecting the reader’s expected experience (referred to as “zero-delta” concept).[10,11] One class involves the use of augmented reality technology to recognize the page using image recognition or the spoken page number using speech recognition. We call this second generation or 2G paper. The other class involves the use of Internet of Things technology comprising printed or embedded electronic sensors such as photodiodes. We call this third
generation or 3G paper. While 2G paper is currently reliable and free, it has a certain awkwardness of use.\[^{12}\] In contrast, 3G paper can lead to more seamless interaction, but is currently limited in terms of sustainability, manufacturability, and cost. In this article, we describe a new approach to supporting 3G paper which addresses these limitations and leads to a variety of cheap, sustainable solutions that are easy to manufacture for printers and publishers. The aim of the proposed solution is to provide a technical solution that increments the value of printed paper by enriching it with additional multimedia assets without adversely affecting the existing reading experience.

1.3. Objectives

First, we are introducing a concept for automatic open-page recognition, which is the main challenge of physically augmented books. After analyzing and comparing our proposed technique with the state of the art, we demonstrate flexible hybrid electronic (FHE) circuits to prototype several open-page sensing solutions and assess the functionality of the system.

Our goal is to demonstrate how the current status of printing techniques for electronics can be utilized alongside hybrid integration to address the requirements of an application specific system.

We are optimizing our solution to address the sustainability, and manufacturability challenges of augmented paper, which will seamlessly link rich digital content to static printed information, thus incrementing paper’s value without compromising its unique physical properties. These challenges include the complicated, expensive, and non-scalable way of assembling the systems proposed in the literature, and the high fabrication cost of the printed electronics that have been used to realize seamless augmentation solutions. The technique we envisage needs to be scalable and robust, and should offer unobstructive augmentation that maintains the “zero-delta” concept, which requires a minimum change from a typical expected interaction with the book.

Finally, we explore additional means of streamlining the augmentation solution, by proposing ways in which the page information data could be integrated within the page graphics, with minimal adaptation of the book printing process.

2. Literature Review

The seamless augmentation of paper does not represent a new problem. In fact, the concept of linking digital and physical copies of documents, and overlaying multimedia content on top of printed information dates to 1993 with Wellner’s Digital Desk.\[^{13}\] The proposed system was using an early form of image recognition and augmented reality to read paper documents on a desk and overlay secondary information or other digital documents. The technology available at the time meant that the system was far from portable and practically had to be installed in an entire room.

With the capabilities of FHE circuits improving rapidly, many applications can utilize the conformability and low cost of printed electronics for solutions that conventional electronic systems cannot address. In fact, according to market research experts at IDTechEx, the demand for FHE systems is expected to reach $3 billion by 2030,\[^{14}\] with applications in smart packaging being \(\approx 60\%\) of the market.

Therefore, with FHE circuits, conformable systems can be fabricated with smaller form-factors that can be better integrated with physical paper objects such as books. However, this technology is at an early stage and cannot be widely adopted, due to reliability and scaling challenges at a fabrication level.

2.1. Core Solutions

Since Wellner’s Digital Desk, two core technologies have been used for linking paper and digital content: (1) augmented reality (AR) solutions, and (2) Internet of Things (IoT) devices.

AR systems utilize the optical recognition of printed markers such as barcodes, QR codes, fiducial markers, or the visual appearance of the actual pages, to trigger actions or digital content on a connected multimedia device, and provide an overlay of digital information on paper books.\[^{13,15–17}\] Examples of such systems, include Webstickers,\[^{18}\] Books with Voices,\[^{19}\] ButterflyNet,\[^{20}\] Magic Book,\[^{14}\] Memento,\[^{21}\] PaperClip,\[^{22}\] and Audiophoto desk.\[^{23}\] ButterflyNet was motivated by the vast amount of information collected by biologists, and helps in the integration of paper notes with digital photographs obtained in the field.\[^{20}\] The Audiophoto desk\[^{23}\] makes use of existing webcams and phone cameras to improve the adoption of the technology and lower the overall cost of each system. Replicate and Reuse\[^{24}\] is the latest AR solution to augmented paper. Photo albums and newspapers are explored through an augmented reality player, which overlays the physical objects with digital content. This technique combines the tangibility of the physical paper with the versatility and rich content of digital media, to create physical interfaces to an always-up-to-date digital world.

Even though image recognition and AR technologies have improved and are being used commercially in various applications, smart paper solutions have not had commercial success yet.\[^{25}\] Such ecosystems require scanning actions with a separate camera or phone, which compromises the reading experience, and cannot seamlessly provide the interaction required for digitally augmented paper. The use of augmented reality glasses or headsets would improve the problematic aspect of the interaction, by removing the need to handle the mobile device by hand. In this work, however, we are providing a viable solution using the IoT approach, to leverage mass market devices in the user’s environment for displaying links.

The IoT approach utilizes sensors embedded in the paper to trigger the digital content directly from the interaction with the physical paper book.\[^{26–32}\] Miniature positional sensors, radio frequency identification (RFID) tags, magnets, conductive inks, buttons, bend sensors, and capacitive touch sensors, have all been previously used to create smart paper and provide a link between the two media types. Active sensing systems in this category include ListenReader,\[^{26}\] the Audioprint Player,\[^{27}\] Paper+++,\[^{28}\] Interactive Newsprint,\[^{28}\] an e-Reader Paper interface,\[^{29}\] and TorBook.\[^{13}\] Listen Reader prototypes use electric field proximity sensors and RFID tags that are incorporated in the book, to identify the open page and provide an enriched experience.\[^{26}\] This immersive content is delivered through a sound
system embedded in a dedicated reading chair that was developed as part of a museum exhibit. Flippin’ replicated the concept with an augmented paper book installation, based on printed capacitive sensors that detect user input on each page and display digital content through an audio-visual playback system. The user evaluation, which was conducted as part of the study, received positive comments from the users that appreciated the physical interaction with the book combined with the immersiveness of the additional content. Another user study concerning augmented books, is TorBook. The study was based on the rough prototype of a smart book, which was far from optimal and marginally integrated with the paper book. Despite the technical immaturity of the proposed system, which was noted as a complaint in the study, the participants recognized the value of the device and the combination of the two media, and reported a satisfactory user experience. Most of the aforementioned systems are handmade prototypes that would be difficult and expensive to manufacture at scale for a commercially successful solution to augmented paper. Additionally, the poor integration of the electronics with the paper nature of the book, results in an unnatural interaction that makes the book feel more like a digital device.

The Anoto pen is a commercially available device, which combines AR and IoT technologies to create an ecosystem for digitizing handwritten content on paper. A miniature optical sensor, control electronics, and a Bluetooth transmitter are embedded in a functional pen. The device recognizes a micro pattern on a special paper and can capture digitally the additional marks that have been made in ink on the pages. Anoto is not directly designed to accommodate paper augmentation, however, there have been attempts to use this technology for turning paper objects into digital interfaces. PaperPoint is a distinctive example, which is utilizing an Anoto pen to control and annotate a live PowerPoint presentation using only a set of printed slides as the interface. The Edfest guide is a similar example that combines an interactive paper brochure, an Anoto digital pen, and a mobile computer to provide supplementary information to the visitors of the Edinburgh Festival Fringe, by interfacing with the printed guide through the digital pen. Despite the commercial availability of the device, these solutions have been singular attempts, rather than sustainable and scalable systems. Additionally, the high cost of the device, in combination with the lack of a complete ecosystem for augmentation, and the additional interaction that the pen requires, make this technology currently unsuitable for accomplishing the unified coexistence of printed and digital media.

2.2. Page Recognition: State of the Art

In this article, we are proposing a technical solution for open page detection that can be seamlessly integrated with paper books. Our aim is to demonstrate how the current status of FHE can be utilized to functionalize and imperceptibly incorporate user interfaces into physical objects for real life applications. We have chosen to address the challenges of augmented paper, therefore, we review later the most recent successful solutions for reliably recognizing the open page of a book without compromising the user’s reading experience.

2.2.1. LightTags

Our first endeavor in the field uses the concept of LightTags for open-page detection. Printed (roll-to-roll) organic photovoltaics (OPVs) are embedded in the paper, serving to recognize the active open page spread of a book. For each page, a unique combination of OPVs is connected to the readout circuit, thus creating a 4-bit code representing uniquely the corresponding page number. The OPV modules are laminated between two sheets of paper to hide them from the user. A wiring-sheet in-between the lamination sheets is used as a spacer, and for electrical connections between the sensors. The assembly is completed with a bespoke binding process to align and connect the signal traces on each page through metallic staples and conductive glue. Figure 1a shows the OPV module before the lamination, and Figure 1b shows the various layers and the result after the lamination process.

The final structure successfully abstracts the electronics from the reader. The LightTags’ sensors (the OPV modules) could then be integrated further, should they be incorporated with the graphics of the page. The lamination of the sensors within paper and the use of vias to connect the electrical signals, maintain the unique feel of the paper. Finally, the photovoltaic sensors utilize the photogenerated voltage (≈100 mV to ≈600 mV under 800 – 1000 lx white light) as the sensor data, therefore, no additional power needs to be delivered to the pages themselves.

However, this method introduces both handling and manufacturability problems to the system. First, the lamination technique, which ensures a paper feel, triples the thickness of each page. As a result, the final page block becomes brittle and harder to handle, which makes the interaction unnatural. Next, the assembly technique for such lamination is manual and requires significant time and effort, which increases the manufacturing cost and complicates any attempt at larger scale.

Figure 1. a) The organic photovoltaic sensors that are laminated between two paper pages for the open page recognition. b) The two paper pages used for the lamination include printed conductors for realizing the connections between the sensors and the spine of the book. A PET sheet, with the same thickness at that of the sensors, is used as a spacer between the pages. Cutouts on the top page are used to allow light to reach the sensors.
production. The cost is further increased by the early technology stage of the roll-to-roll-printed OPV modules.[16] Finally, embedding the sensors between the pages is an irreversible process, which makes the augmented book incompatible with existing recycling processes, considering the printed conductive ink on the pages and the challenging delamination of the sensors and the plastic spacer from in-between the paper pages.

2.2.2. Digital Bookmark

The latest and most technologically advanced solution was presented by Bailey et al. in the form of a Digital Bookmark.[37] The proposed system is combining printed conductors on the pages of a book with commercial electronics, to synchronize paper- and screen-based versions of the same content.[37] A unique conductive pattern is printed on each open page spread, and the electronics that attach to the top of the book and across the conductive pattern can translate the printed code into a page number. Even though the page recognition is robust, the device is bulky, the interaction requires the user to unclip, align, and clip the reader for each page flip, and the book cannot be manufactured sustainably, because conductive ink needs to be printed on each page, thus increasing the fabrication costs, and reducing the recyclability of the system.

3. Results and Discussion

3.1. The Magic Bookmark—Overview

The Magic Bookmark was devised as an improved open page detection technique, which addresses the handling and sustainability problems of the latest work in the literature: LightTags and the Digital Bookmark.[37] Prototypes are designed to be compatible with the NGP ecosystem.[11] The device consists of a flexible strip augmented with sensors that automatically detect the open page, while being used as a typical bookmark. Each page contains a unique binary code near the book’s spine, which is then discerned by the electronically enhanced bookmark and transmitted via a bespoke printed circuit board to an adjunct device that runs the NGP application. The concept and user journey are shown in Figure 2. By reducing the modifications required to the physical book, the interaction is improved from both the existing NGP technical solution and Bailey’s approach with the digital Bookmark.[11,37]

In this article, we are presenting three techniques for automatically recognizing the open page of a book, applicable to both soft and hard cover volumes. The following sections introduce the three solutions and discuss the functionality of each method as well as potential limitations.

3.2. Technique 1: Printed Conductive Switches

This method relies on printed conductive patches on the pages of the book. An array of patches creates a unique pattern on each page and interdigitated conductive electrodes printed on the bookmark are short-circuited when placed on the open page. Figure 3a shows the concept diagram. The conductive switches can be connected in a resistive digital to analog configuration leading to a single analog-to-digital Converter pin on the microcontroller, as shown in Figure 3b. Alternatively, each switch can be connected directly to a microcontroller general purpose pin, as shown in Figure 3c. This solution is similar to Bailey’s approach,[16] but is targeted for a different application in a more accessible form factor.

Several challenges arose when creating a prototype (see photographs in Figure 3d). For the recognition to be robust, precise bookmark alignment is required, as is firm adhesion on the page. This is one of the reasons why Bailey’s approach is comparatively bulky and needs mechanical pressure to affix the reader onto the page. We attempted to address this problem by utilizing magnets for the alignment. While successful in providing accurate positioning, this made the device harder to operate and challenged the scalability of the ecosystem to thicker books with more pages. Separately, moderate concerns emerged regarding the printing of unique combinations of conductive patches on each page. While this can easily be accomplished in modern digital printing processes, its implementation substantially reduces the manufacturability and recyclability of the device. Printing and binding would need to accommodate for the deposition and sintering of conductive ink, which results in increased fabrication costs and higher barriers to entry for a commercially sustainable ecosystem.

We concluded that the downsides enumerated earlier outweigh potential advantages brought about by the content augmentation,
and decided to abandon this line of investigation. As such, no in-depth functional or reliability measurements were performed.

3.3. Technique 2: Optical Recognition with Physical Page Cut-Outs

The main shortcomings of the aforementioned technique, specifically the requirement to print conductive traces on each page and the potentially unreliable electrical contact between bookmark and page are addressed by implementing optical detection. This technique uses physical cut-outs within the paper which represent a unique binary code for each page. The opacity of a single sheet of paper is sufficient to create optical contrast readily detected by the augmented bookmark which is populated with a series of photodiodes. In this setup, the bookmark is operated by positioning behind the page that is currently read by the user (see Figure 4a) being firmly held between two pages near the spine of the book. This arrangement also ensures reduced light leakage behind the currently open page.

The photodiodes are used in photovoltaic mode, meaning that the photogenerated voltage of each diode is read by the control electronics. A reference sensor at the top of the bookmark always remains exposed through an opening on the paper. The voltage from each sensor is compared against a proportion of the reference photodiode voltage to distinguish diodes directly exposed to light from ones covered by paper. The use of an always exposed reference sensor also permits using the device under any lighting conditions without significant errors in the binary detection.

The control electronics module translates the optical binary code and transmit it to the proprietary application. This module can be combined with the bookmark, or incorporated within the book’s cover. The circuit design of the control electronics used can be seen in Figure S2, Supporting Information.

In combination with the NGP’s ecosystem for publishing, linking, and maintaining the augmentation content, this technique creates a robust and complete solution to the coexistence of physical books and digital media, without compromising the paper feel. It eliminates the need to instrument every page, greatly simplifying the manufacturing process, compared to technique 1 or any other solution in the state of the art.

Concerning scale-up and manufacturability, this version of the bookmark can be realized with low-profile, widely available off-the-shelf photodiodes. The configuration is simple (Figure 4b) and can already be made on a flexible substrate with existing conventional fabrication techniques (copper etching and automatic pick and place on a flexible printed circuit board). Photographs of the prototypes in use can be seen in Figure 4c,d. However, the use of cut-outs on the paper, makes the printing and binding process of the book more challenging, as the aligned perforations or cut-outs will require additional equipment and steps, increasing fabrication time and cost.

From an interactivity viewpoint, placing the device on the page after the open one differs from a typical interaction with

Figure 3. Magic Bookmark technique 1: Printed conductive switches. a) The concept of this method is based on conductive switches within the bookmark, which are triggered by a unique combination of conductive patches on each page. b) The printed switches (S1, S2, S3, and S4) can be configured as a resistive digital to analogue converter, which would only require a single MCU analog to digital converter input to decode the page information. c) The printed switches (S1, S2, S3, and S4) could be connected directly to general purpose input/output pins of the microcontroller, using its internal pull-up resistors. This would require fewer components to be integrated on the bookmark device, but more pins, thus a larger microcontroller package, for books with many pages. d) Photographs of the prototyped printed switches on the surface of the bookmark.
bookmarks and deviates from the zero-delta concept that we are striving to achieve.

Video S1, Supporting Information, shows the working technique 2 prototype. We are not reporting exhausting testing data, as this optical readout solution has been demonstrated in the past in the NGP ecosystem\[10\] and in primitive, unpublished LightTags implementations for interactive packaging.\[38\] Video S2, Supporting Information, shows a short comparison between the NGP technical solution and the Magic Bookmark with technique 2.

While this technique has obvious functional merits, the relatively cumbersome interaction demanded further improvements, which we address in our final solution.

### 3.4. Technique 3: Visual Pattern Recognition On-Page

This technique is addressing the fabrication and interaction issues of the previous methods. Here, the bookmark comprises reflective optical sensors to detect a contrast pattern printed on each page near the spine of the book, which encodes uniquely that page’s number (Figure 5a). The sensors consist of an infrared light emitting diode and an infrared sensitive phototransistor. When the control electronics make a page number query, all diodes on the bookmark illuminates the paper page, and the phototransistors capture the reflected light at each location. The transistor’s output is wired to a microcontroller pin through a pull up resistor (Figure 5b). The optical properties of the area of the page “seen” by each phototransistor influence the amount of infrared light detected. The common source configuration converts current to voltage, which is finally used by the microcontroller input to determine the binary state of that bit. The circuit of Figure 5b is arrayed across the bookmark to allow for a binary code commensurate with the total number of sheets in the book to be generated.

To improve the readout reliability, the final structure is encapsulated with a flexible polymer (200 μm of PDMS), as shown in Figure 5c, which acts as a light guide for the reflected light, and providing sufficient vertical separation between the sensor and the page to allow light generated by the photodiodes and scattered by the page to be collected by the phototransistor. A close-up of example of the final structure is shown in Figure 5d.

The simplest means of realizing the printed contrast pattern is via printing black toner or ink, similar to a conventional bar- or QR code. The device was prototyped and tested in a variety of

![Figure 4. Magic Bookmark Technique 2: Optical recognition with physical page cut-outs. a) This concept requires physical optical cutouts that create a unique pattern on each page. The bookmark is then placed after the active page, to detect which of the photosensors are exposed to light. b) Utilizing the photogenerated voltage of the photodiodes simplifies the circuit diagram. This technique requires fewer components, but more analogue input pins (or a multiplexer) are needed for decoding the pattern. c) A prototype notebook shows how the system would be used in practice. d) The system has also been adapted to a printed copy of the augmented book content, and tested with the previously developed NGP ecosystem.](www.advancedsciencenews.com)
different light conditions and with contrast patterns realized with several colored and special pigments.

The first metric we have assessed is the bookmark’s ability to detect black and white patterns on standard paper. A sensor (Figure 5d) was positioned above paper with black and white areas at different contact angles. Figure 5e shows the various angle and color combinations. The graph in Figure 5f summarizes the measurements (each data point plotted represents the average of 100 measurements under the specified angle). The results indicate that, with a power supply of either 5 or 3.3 V, the black and white pattern can be detected for an angle up to 45°. For higher contact angles, the output of the sensor when

![Figure 5.](www.advancedsciencenews.com)

Figure 5. Magic Bookmark Technique 3: Visual pattern recognition on-page. a) Optical contrast sensors are used to discern a pattern printed using graphical inks or toners on each page, next to the book’s spine. b) The circuit for each bit combines an infrared photodiode and an infrared phototransistor, biased individually using a resistor. c) The multilayer circuit is realized using conductive silver ink on a flexible polyimide substrate. Polyimide tape is used to isolate the different layers of the circuit, and a polymer encapsulation layer as a final step is used to protect the device and simultaneously act as a guide for the emitted and reflected light. d) Detail of the final structure after component assembly and encapsulation. e) The device was tested on black and white paper under different angles to simulate real use conditions. f) Average outputs of 100 samples taken for each of the instances shown in (e) for a 3.3 V and a 5 V supply. The device can reliably distinguish between black and white patterns for either supply, if the contact angle remains under 45°. More statistical data based on the complete dataset can be found in Figure S4, Supporting Information. g) Measurements for different levels of black opacity. The sensor response is not sufficient to distinguish between close grey levels, but opacity down to 30% can be used reliably to determine between the two states. h) A similar test to (g) was conducted for the primary colors (Cyan, Magenta, and Yellow), and compared against the black and white marks. Yellow has a response equivalent to white, and cyan or magenta have a response equivalent to black. i) The relative reflectance of the main colors was verified using a spectrometer, to support the results in (h). The sensor’s relative spectral sensitivity is also overlaid on the graph.
reading a white page is close to saturation and can be significantly harder to distinguish from the equivalent black page. This technique can offer good error margin (smallest average voltage range between black and white thresholds for an angle from 0° to 45° and a 5 V supply is 0.44 V or 8.8% of the supply), but the number of components increases by 4 (one photodiode, one phototransistor and two biasing resistors as shown in Figure 5b) with every doubling of the number of sheets within the augmented book (Equation (1)).

\[ n_{\text{components}} = 4 \log_2 n_{\text{pages}} \]  

(1)

The number of components can be reduced, and the overall device optimized further by representing more than two states with each sensor. Different levels of grey or different colors can be used as part of the optical code printed on the page, which would lead to more pages being distinguished per sensor. This approach would additionally allow for the code to be creatively incorporated with existing graphics, or as a minimum to be generated in an aesthetically pleasing form.

Thus, the second metric that we assessed was the use of the sensor to detect different colors and a greyscale gradient against a white background.

We tested the sensor with densities of black from 10% to 100% with 10% increments, and the three subtractive primaries; cyan, magenta, and yellow. The results for various opacities of black are shown in Figure 5g, which indicates that densities from 30% to 100% of black cannot be reliably discriminated. The gain of the common-source phototransistor stage results in the various levels of black being registered as logic high by the processor. The results from the color test are summarized in Figure 5h, which shows that colors cyan and magenta respond equally to black, and yellow responds equivalently to white. On the one hand, this binary response improves the reliability of the device when it is being used, but on the other hand, the different densities or colors cannot be used for reducing the number of components using the present approach. This could be improved by fine-tuning the distance between the sensor and the page, but this would be impractical for a typical bookmark use case.

Based on these two graphs (Figure 5g,h), shades of grey and different colors could be used, in principle, for the optical code, which could be integrated better with the graphics of the book, making it easier to further conceal the technology from the user.

The response of the different color pigments was also confirmed using a spectrometer. The reflectance of each color (plain white paper, and black, cyan, magenta, and yellow pigments) is shown in Figure 5i. An approximation of the sensor’s relative spectral sensitivity is also overlaid on the figure. The results confirm that yellow does indeed have a similar response to white at wavelengths detected by the sensor. The reduced reflectance of the cyan color under the 800 nm wavelength mark does not fully justify why it responds similarly to the color black, considering that the sensor’s high sensitivity over the range 800 to 1000 nm would dominate the output. Also, the output measured for the magenta samples in correlation to the measured optical reflectance likewise does not justify the sensor’s response.

However, due to the amplification of the signal by the phototransistor, this would indicate that the system has a sensitivity threshold of ≈75% reflectance at wavelengths between 750 and 1050 nm, where the output changes from logic high to logic low, which appears to correlate with the observed response for colors cyan and magenta.

Multiple tests have indicated a consistent reading from each of the sensors used. However, the correlation of the detector’s output and the reflectivity of each color pigment is based on statistical figures provided by the manufacturer of the sensor. Conceivably, actual parameters individual sensors could indeed differ from typical values according to the datasheet, or even changed by the manufacturer without further notice. Since this is not intrinsically a reliable detection method, sensor biasing may be optimized for distinguishing between different primary colors. Additionally, the optical characterization indicates that using selective sensors or color filters on top of the existing sensors to further narrow their spectral sensitivity (at key

Figure 5. Continued.
wavelengths in the visible spectrum, such as 400, 550, and 700 nm) would naturally permit the more accurate and reliable detection of primary pigments. Certainly, in a commercial system, the emissive and photosensitive devices would be co-optimized together with the specific graphical inks used.

### 3.4.1. Towards Unobtrusive Printed Pattern Recognition

To further abstract this third open page recognition technique form the user, we have investigated the use of an infrared (IR) blocking, visible-transparent ink, which, when printed on white paper would be able to absorb the transmitted light from the sensor’s light emitting diode, and simultaneously be highly reflective at the visible wavelength range, making it practically invisible to the reader. A commercially available ink with such properties (PrintColor SC-140-AI/0761) was tested with the Magic Bookmark’s sensor to determine the practicality of this method of detection. Different concentrations (100%, 70%, 50%, and 30%) of the ink were assessed, as the aspect differs noticeably with concentration (Figure 6a). The voltage output of the Magic Bookmark that was recorded for the different concentrations of the ink is shown in Figure 6b, which indicates that the sensor indeed reacts to the custom infrared absorbent

**Figure 6.** a) Photographs of samples of the SC-140-AI/0761 ink (PrintColor) used for this evaluation, printed on standard white paper, in various ink concentrations (Version 1 = 100%, Version 2 = 70%, Version 3 = 50%, and Version 4 = 30%). By diluting the ink further, and using an off-white-colored paper, the printed pattern can be made almost invisible to the reader. b) Average outputs of 100 samples taken with the Magic Bookmark sensor against different backgrounds (black, white, and various concentrations of the SC-140-AI/0761 ink), with a 3.3 V and a 5 V power supply. The infrared absorbent ink produces a similar effect to the black pigment, and the electrical output is sufficiently different from the sensor’s response to the plain white paper. c) Reflectance (%) vs. wavelength (nm) graph for black photocopier toner, white paper, and the SC-140-AI/0761 ink (in different concentrations) was verified using a spectrometer, to support the findings in (b). The sensor’s relative spectral sensitivity is also overlaid on the graph. These results indicate that the detection method could be successful even if the SC-140-AI/0761 ink is further diluted, as a layer that is almost transparent in the visible range can be obtained, while maintaining high absorbance across the sensor’s bandwidth.
pigment similarly to a regular black pigment. Spectral analysis of the IR-blocking ink, shown in Figure 6c, confirms the low reflectance across the bandwidth of the detector. As the ink is diluted, its transparency in the visible increases significantly, but its reflectance in the infrared region remains low. Therefore, we expect that by further diluting the ink, a pattern with high IR contrast that is practically imperceptible to human readers may be created. The use of off-white paper or the printing of conventional graphical ink with a similar visible response would also contribute to entirely abstracting the technology from the user of the augmented book, as far as the aspect of the page is concerned.

This third implementation technique for the Magic Bookmark is the closest solution to a zero-delta interaction, as the reader simply places the bookmark on the active page and the recognition is automatic without any further user action.

3.5. Magic Bookmark Techniques: A Summary

We have proposed and discussed three distinct techniques for automatically recognizing the open page of a book. In the first technique, the bookmark contains an array of printed conductive switches triggered by contact with conductive patches on the paper pages. This technique is similar to Bailey’s Digital Bookmark[37] which is considered technologically the state of the art at recognizing an open page. Despite the low number of off-the-shelf components needed for this implementation, the fabrication costs are high, and the recognition is prone to errors. The second technique uses optical sensors to detect openings on the paper. This method is robust and offers low error rates. Simultaneously, the handling of the augmented book and the functional bookmark, as well the fabrication of the system is more streamlined and less cumbersome compared to both the Digital Bookmark[37] and the LightTags.[11] However, the interaction remains further away from the zero-delta concept we are aiming to achieve, as the user needs to place the device on the page after the one being read. The last technique uses reflective optical sensors to detect a unique contrast pattern printed on the current page. A proprietary transparent infrared-absorbent ink can be used to create the pattern, making it invisible to the user, thus further abstracting the technology. This technique is even simpler to fabricate compared to the second method, since no paper cutouts are needed. Additionally, the interaction is more natural since the electronic bookmark can be placed on top of the active page, just like a normal bookmark. Therefore, compared to the latest techniques in the literature (Digital Bookmark[37] and LightTags[11]), the last method proposed in this work provides a better integrated interface to the digital world through paper, and is easier to manufacture at scale. Table 1 summarizes the advantages and disadvantages of each technique.

Table 1. Summary and comparison of the three methods for realizing the Magic Bookmark concept.

| Magic Bookmark Technique | Advantages | Disadvantages |
|--------------------------|------------|---------------|
| 1. Printed conductive switches | Low material costs, less off-the-shelf parts required | Requires conductive ink on each page, harder and more expensive to manufacture at scale |
| 2. Optical recognition with physical page cut-outs | Robust recognition and low error rates, widely available parts | Device needs to be placed on the page after the one being read, interaction away from zero delta concept |
| 3. Visual pattern recognition | Zero delta concept | Light variation issues resulting from the sensitivity of the sensor to different environmental light and contact angles with the paper |

Optimization of functional printed transistors and photosensors that can be manufactured reliably at the required scale for this ecosystem. Simultaneously, the design of the proof-of-concept prototype will be iterated and optimized for medium scale fabrication using conventional components, including bending and abrasion tests. Readout timing will be optimized for energy efficiency and to reduce false readings during bookmark repositioning.

One advantage of Technique 3 is that the bookmark unit is completely self-contained and independent of the paper block and binding. This makes it suitable for detachment and even reuse with other books, for recycling. This is a major advantage of the technique in its own right since embedding electronics more pervasively in each page of a book, could create a problem for recycling and consequently environmental sustainability. We aim to explore this further how to dispose of or reuse the bookmark unit itself.

Several working prototypes embedded in full-scale books will be used to test our statements regarding functionality and usability in small-scale user studies designed to assess the system’s fit to user behavior. The approach is based on the assumption that users are comfortable with using bookmarks as part of a reading experience, and repurposing this to provide extra functionality and augmentation. The extent to which this is true needs testing and may lead to additional interface ideas and innovations such as using the bookmark to indicate the position of hotlinks on a
page or as a tactile user interface for controlling media playback on screen.

5. Conclusions

An ecosystem for the coexistence of printed and digital media that is incorporated with paper books without disturbing the readers’ experience is not fully addressed by the current state of the art. In this article, we have used the emerging technology of flexible hybrid electronic circuits to present the Magic Bookmark; a seamless open page detection technique for augmenting soft and hard cover books. In this article, we provide an assessment and a comparison of the various iterations of the Magic Bookmark. A bookmark which comprises reflective infrared sensors coupled with contrast patterns printed with graphical ink represents the best compromise between system complexity, manufacturability and deviation from conventional user expectations. Additionally, we have reviewed the system’s response to different shades of grey, colors, and a special transparent ink that indicate how the Magic Bookmark and the necessary optical code can be seamlessly integrated with a printed book, both visually and functionally.

The proposed device is better integrated, more sustainable, easier to fabricate, and provides an improved interaction, compared to the state of the art. It is a modular system, in which the book printing process and end-of-life disposal are greatly improved over current solutions, largely by eliminating the need of functionalizing the book’s pages with active electronics or conductive traces. Our previous approach embedded the control electronics within each book’s hard cover. The standalone control unit developed here drastically reduces redundancy and enables use with both soft- and hardcover books and even magazines and leaflets. This broadens the practicality of our augmentation concept from high-value, costly hardcover books to more versatile, transient, and low-cost form factors.

The subsequent development step is to utilize fully inkjet-printed active devices that will replace the sensing elements of the bookmark. Finally, the active devices will be integrated with conventional control electronics, to provide an optimized paper augmentation system that sustainably combines the functionality of silicon circuits with the flexibility and conformability of novel printed electronics.

6. Experimental Section

Fabrication and Integration: Printed conductors and hybrid integration of conventional components have been used to prototype the three different page detection techniques. In each case, the circuit layout has been optimized for dispenser printing with a Voltera VOne printer. A multilayer approach was used to realize the circuits, which is shown in Figure S1, Supporting Information. A polyimide film is used as a substrate for its flexibility and its resilience to high temperatures. Two layers of silver nanoparticle based conductive paste (Voltera Flex 2) are printed, with a piece of polyimide adhesive tape between the intersections of the two layers. The silver ink was sintered at 200 °C for 40 min. Lead free solder paste, dispersed using the Voltera VOne printer, is used to attach the components on the pads with a typical reflow process. Finally, the device is encapsulated within a silicon-based organic polymer (Polydimethylsiloxane [PDMS]), which protects it during use and acts as a light guide for the optical sensors.

Components: For the control electronics used to obtain the sensor data and to interface with the Next Generation Paper ecosystem,[1] an Atmega328P microcontroller was used, in combination with a RN42-I/RM Bluetooth module. The circuit diagram and printed circuit board design can be found in Figure S2, Supporting Information. Technique 2 was prototyped with both SFH2240 and SFH2716 photodiodes. Technique 3 was tested with SFH9206, VCN72020, and HSFL-D9100-021 reflective sensors (the evaluation board and corresponding schematic can be seen in Figure S3, Supporting Information), with the SFH9206 being used for the experiments described here. The black, cyan, magenta, and yellow pigments were printed on paper using a Samsung MultiXpress SL-X4300LX and toner cartridges CLT-K506, CLT-C506, CLT-M506, and CLT-Y506, respectively. The infrared absorbing ink was the Printcolor Screen Ltd SC-140-AI/0761 spectraCARD IRB.

Electrical and Optical Characterization: The relative reflectance of the black, cyan, magenta, and yellow colors, as well as that of the spectraCARD IRB ink, were obtained using a Cary 5000 UV-vis and NIR spectrometer. The voltage for the black and white angle test, and the SC-140-AI/0761 ink was obtained using a Tektronix DPO2024 digital oscilloscope. Electrical measurements of response to patches of various opacities of black, as well as the cyan, magenta, and yellow colors were automated using an Arduino, and the results were calibrated against an RS PRO RS12 multimeter.

Ink Formulation and Deposition: The commercial infrared-blocking ink (Printcolor Screen Ltd, SC-140-AI/0761 spectraCARD IRB) was manually screen printed on standard printer paper using a 90-48 mesh in concentrations of 100%, 70%, 50%, and 30%.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

augmented paper, computer human interfaces, hybrid integration, printed electronics, user interaction

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