# WonderLens: Optical Lenses and Mirrors for Tangible Interactions on Printed Paper

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## ABSTRACT
This work presents *WonderLens*, a system of optical lenses and mirrors for enabling tangible interactions on printed paper. When users perform spatial operations on the optical components, they deform the visual content that is printed on paper, and thereby provide dynamic visual feedback on user interactions without any display devices. The magnetic unit that is embedded in each lens and mirror allows the unit to be identified and tracked using an analog Hall-sensor grid that is placed behind the paper, so the system provides additional auditory and visual feedback through different levels of embodiment, further enhancing the interactivity with the printed content on the physical paper.

### Author Keywords
Paper, Lens, Mirror, Optical Illusion, Tangible Interaction.

### ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

## INTRODUCTION
Tangible user interface (TUI) [6] are enabled on portable displays, such as tablet PCs [12, 20], to facilitate users' interactions with digital content. Paper, which is lightweight and versatile, is also a highly portable display. Most people still feel that physical paper are more comfortable for reading and playing than electronic displays (such as e-paper, LCDs). Paper also affords natural user interactions, because our interactions with paper builds upon our "pre-existing knowledge of the everyday, non-digital world" [7]. However, since the content that is printed on paper is static, it constrains the interactivity of printed paper.

Previous researches have increased the interactivity of printed contents on paper, for example, by applying mechanical movable structures [4] or augmenting information on the paper by using machine readable formats, such as magnetic stripes [8, 11]. Augmented Reality (AR) methods provide more seamless experiences by using a camera-projector system to project images onto paper [16, 17, 19] or provide camera-mounted handheld devices or HUDs [2] that enable users to explore the augmented visual content on the paper. Although AR-based methods support rich and interactive content, the need for additional display devices and/or external sensing mechanisms may reduce the immersion enjoyed by the interacting users. To increases immersiveness, Listen reader [1] allows users to explore the audio information that is in a specifically designed book, which is based on proximity and RFID sensing. Jabberstamp [15] enables children to associate recorded audio with paper drawings by using a stylus, which is based on electromagnetic resonance (EMR) sensing. However, without dynamic display capabilities, these systems provide only auditory feedback.

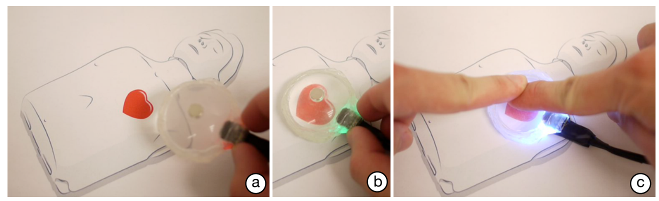

**Figure 1. Immediate visual feedback provided by an LED-mounted *flexible convex lens*. (b) In a CPR learning program, the lens blinks to red to prompt the user to place the lens on the heart that is printed on the paper. (c) The heart is magnified to prompt the user to start. (d) The user presses the lens to generate pulses, making the heart contract; the progress light then changes.**

This work presents *WonderLens*, a system of tangible lenses and mirrors that supports tangible interactions on printed paper. When users perform spatial operations on the lenses and mirrors, these components distort the printed content, providing dynamic visual feedback without the need for additional display devices. In each of lenses and mirrors is embedded a specifically designed magnetic unit, allowing the system to track their types and states of the optical components in real time using an analog Hall-sensor grid that is attached to the back of the paper. Accordingly, the system can improve user experiences by providing more auditory and visual information for users.

Figure 1 shows an example of interactive CPR learning to illustrate the proposed idea. When a user moves a PDMS (poly-dimethylsiloxane)-made *flexible convex lens* to a desired position, the heart that is printed on the paper becomes


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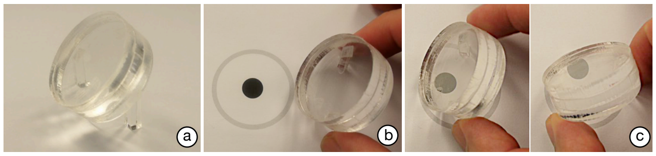

**Figure 2. (a) *Tilted cylindrical lens*. (b) Optical refraction causes an offset on the circular symbol, and therefore displays the orientation of the lens.**

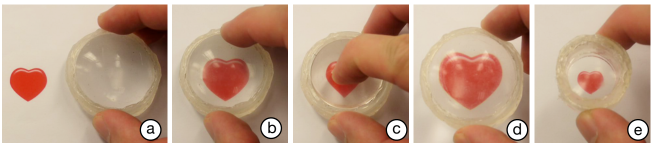

**Figure 3. *Convex lens* and *concave lens*. (a) With an air gap beneath the convex lens, the convex lens (b) magnifies the underlying content. (c) Pressing the *flexible* convex lens reduces the magnification ratio. (d) Lifting the convex lens increases the magnification ratio. (e) Lifting the concave lens increases the shrinkage ratio.**

larger to prompt the user to continue. When the user presses and releases the lens, the user can perceive not only the printed heart contracts through the lens, but also the progress indicated by blinking point light and simultaneous heartbeat sound. This example shows that the tangible lens provides seamless user experiences of the information that is embedded in printed paper.

## EXPLORING USES OF OPTICAL LENSES AND MIRRORS

This work begins with an exploration of optical lenses and mirrors. Various lenses and mirrors are fabricated by laser-cutting acrylic and molding PDMS – the material that is conventionally used to make disposable contact lenses. Analyses of their optical features and physical affordances revealed that some lenses and mirrors can provide dynamic visual feedback in the corresponding operations because of the optical illusions that they can cause. Five basic types of optical components and their corresponding visual effects are identified as the most useful and comfortable for user interactions. Simple graphical design guidelines for them are provided hereafter.

The *tilted cylindrical lens* (Figure 2) is made of a transparent acrylic cylinder. Tilting the cylinder causes it to refract the underlying graphical content, causing a small offset of that content from its actual position. The offset is proportional to both the angle of tilt and the thickness of the cylinder. Rotating the cylindrical lens results in an visual illusion of rotation, which can be perceived over a wide range of viewing angles. Circular symbols are effective for illustrating this effect.

A *convex lens* magnifies the underlying graphical content, whereas a *concave lens* shrinks the underlying graphical content, as shown in Figure 3. The size of the magnified content is proportional to the distance between the bottom of the lens and the paper. Fabricating them using PDMS and maintaining an air gap beneath them allow users to *press* them to change the magnification or shrinkage. Symbols that are smaller than the lenses are effective for illustrating this effect.

*Prism* (Figure 4) duplicates content in a manner that is determined by its median line. The distance between the duplicated images is determined by the angle and height of the prism, and also the distance between the bottom of prism and the paper. Translating or rotating a prism also produces optical illusions over a wide range of viewing angles. Symbols that exhibit reflective symmetry and simple lines are effective for illustrating this effect.

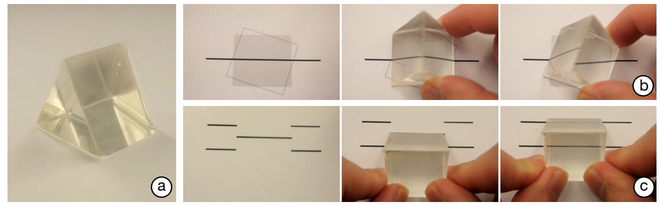

**Figure 4. (a) *Prism*. (b) Rotating a prism on a line to break it. (c) Moving a prism on the lines to connect them.**

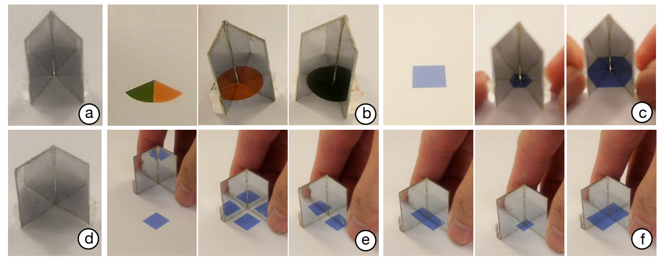

**Figure 5. *Angled mirrors*. (a) $\pi/3$ angle mirror. (b) Rotate a $\pi/3$ mirror to select and complete different sectors. (c) Move a $\pi/3$ angled mirror to proportionally scale a hexagon. (d) $\pi/2$ angle mirror. (e) Move a $\pi/2$ angled mirror to generate several replicates. (f) Move a $\pi/2$ angled mirror to non-proportionally scale a rectangle.**

*Angled Mirror* (Figure 5), formed by two mirrors that face each other but at a certain angle rather than directly, can complete a partial content or generate several replicates of the content. The applicable principle is similar to that of a kaleidoscope: the visual effect of optical reflection is determined by the position of the angled mirror and the angle that is formed by the two mirrors. Symbols that are customized for differently angled mirrors can provide visual feedback on rotations and translations.

Based on the guidelines described above foregoing information, designers can incorporate the specified symbols into their designs of graphical content, allowing users to explore the hidden information using the lenses and mirrors.

## SENSING THE LENSES, MIRRORS AND PRINTED PAPER

A sensing platform is developed to investigate the possible interactions between lenses, printed content, and digital information. To sense the near-surface interactions that are performed using optical lenses and to maintain their transparency, a specially designed permanent magnetic unit is attached to each optical lens as shown in Figure 6. The magnetic units carry essential information about the different types of lenses, including the ID, position, and orientation. The magnetic unit is also carefully located to maximize the transparency of each lens. An analog Hall-sensor grid [13] (Figure 7a), which consists of $21 \times 32 = 672$ Winson WSH136 analog Hall sensors, is measured in 2mm thick with an 21(W)$\times$16(H) cm$^2$ sensing area, which is placed behind

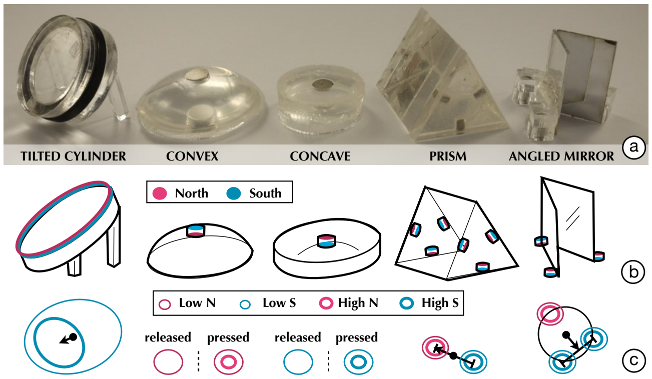


**Figure 6. (a) Optical lenses and mirrors that have embedded magnetic units. (b) Placement of magnets in each of lenses and mirrors. (c) Resulting features of the magnetic field images.**

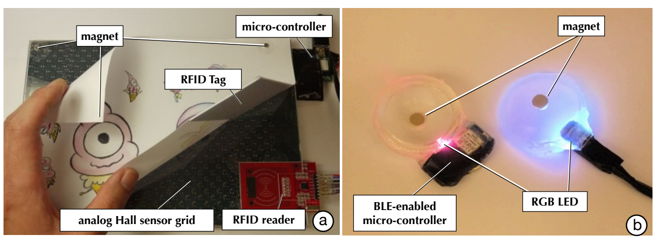


**Figure 7. Hardware. (a) Paper and sensing platform. Wireless and wired LED-mounted flexible convex lens.**

the paper to track the magnetic unit in each lens, using the sensing algorithm that was proposed by GaussBits [12], and to identify the types of each lens from the features (e.g. blob sizes and positions) that are extracted from the magnetic-field image.

To realize the functionality of a piece of printed paper while modifying it as little as possible, to each piece of paper in this study is attached an RFID tag and two small magnets. An RFID reader and two magnets are also attached to the sensing platform to sense the presence and determine the ID, as shown in Figure 7a. The small magnets allow users to easily snap the paper onto the sensing platform for ease of alignment. The system recognizes the RFID tag of the "snapped" piece of paper and loads the corresponding digital information to enable user interactions.

## ADDITIONAL AUDITORY AND VISUAL FEEDBACK

In addition to the optical illusions that are provided by the lenses and mirrors, the system can provide additional feedback that enriches interactivity and facilitate communications between the users and the system. With reference to Fishkin's taxnomy of different levels of embodiment in TUI [3], the proposed platform provides additional auditory and visual feedback for three different levels of embodiment. With regard to auditory feedback, the system provide *environmental* sounds using the speaker of the laptop to which the sensing platform is connected. With regard to visual feedback, besides the optical illusions that are fully embodied in the lenses, an additional low-power consumption full-color LED is embedded into the LED-mounted flexible convex lenses

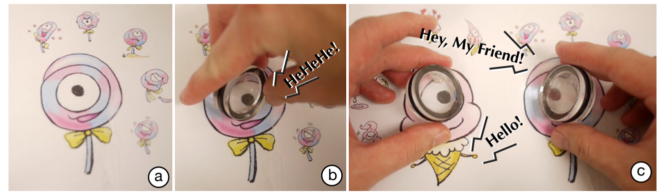


**Figure 8. (a) Interactive storytelling application. A user (b) rolls the character's eye by rotating the tilted cylindrical lens, and the character tells user what he sees. (c) Two characters chat when they are looking at each other.**

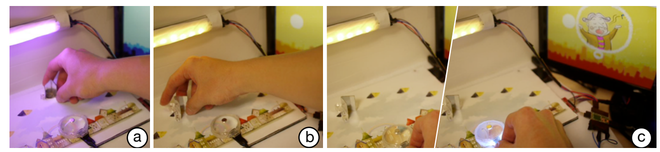

**Figure 9. (a) Hide-and-Seek game. A user (b) places an angled mirror on a sun symbol to set the time to 10am, changing the ambient light and presenting the detail view on the remote display. (c) The user moves an LED-mounted convex lens to find hidden characters. Once found, the lens glows to prompt the user to check the remote display to see which character has been found.**

to provide simple visual hints *nearby* the printed content, as shown in Figure 7b. Also, a full-color LED strip that can be easily attached to a lamp or a wall provides *environmental* ambient light, and a laptop display provides rich visual information that is *distant* from the users.

## APPLICATION EXAMPLES

Based on the implementation described above, the utility of the lenses and the additional visual feedback are illustrated using three examples, according to the different levels of embodiment. Auditory feedback were provided for all examples.

*Storytelling* (Figure 8). In the interactive storytelling program, a user places a *tilted cylindrical lens* on a character's eye. Optical refraction shifts the character's eye to the side toward which the lens is tilted. The user rolls the character's eye by rotating the lens, and the character vocally tells the user what he sees. When the two characters in the story look at each other, they chat. This example shows how the lens functions using *only auditory* feedback.

*CPR learning* (Figure 1). In the CPR learning program, a user places an LED-mounted *flexible convex lens* on a patient's heart that is printed on the paper, and the user sees the blinking heartbeat light signals through an embedded point light, while simultaneously hearing the heartbeat. The user saves the patient by pressing and releasing the soft convex lens at a constant rate. While providing the pulses, the user can see the patient's heart contractions and monitor progress by observing the light. This example shows how the lens works with additional visual feedback *nearby* the printed content.

*Hide-and-Seek* (Figure 9). In the hide-and-seek game, a user places an *angled mirror* on one of the hybrid sun (day)-and-moon (night) symbols on the paper to set the time of the story. When the angled mirror has been placed, it reflects the whole image of the selected part of the symbol, the ambient light changes in intensity and/or type, and the remote display shows an evocative scenario. In each scene, users can move an LED-mounted *convex lens* on the paper to find hidden characters out. When a character is found, the lens glows to prompt the user to check the character's details on the distant display, which is located in front of the user. Using the mirror to select another time changes hidden characters' positions again. This example demonstrates the operation of the lens and mirror with additional *environmental* and *distant* visual feedback.

## CONCLUSION AND FUTURE WORK

This work has presented *WonderLens*, a system of lenses and mirrors that augments tangible interactions with printed materials. Five basic components, a proof-of-concept system, and several extensions are proposed to demonstrate possible tangible and embodied interactions. Future work should consider the fabrication of advanced lenses by CNC milling or 3D printing [14, 18] to provide more features; the use of an advanced process to manufacture analog Hall-sensor grid or 3D LC-Tag sensing [5] to reduce the cost of the sensing platform, or the combination of lenses and mirrors with circuit printing [10] and an energy harvesting mechanism [9] to further enhance the interactivity of printed paper.


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