PicPop: A pop-up picture book comprising mid-air images

AYAMI HOSHI, The University of Electro-Communications, Japan
SHUNJI KIUCHI, The University of Electro-Communications, Japan
NAOYA KOIZUMI, The University of Electro-Communications, Japan

In this study, we propose PicPop, a pop-up picture book system that uses mid-air images to make digital images pop out from a flat picture book. The user does not need to wear a special device to have an interactive experience with pop-up picture books that employ the proposed system. A reflective type of paper is used to turn the book into a display surface for projecting mid-air images onto. Furthermore, we realized a reduction in the overall volume of the system as compared to the conventional reflective mid-air image-display method, while retaining the desired luminance of the mid-air images.

CCS Concepts: • **Human-centered computing** → Mixed / augmented reality; Displays and imagers.

Additional Key Words and Phrases: mid-air image, pop-up picture book, mixed reality

ACM Reference Format:
Ayami Hoshi, Shunji Kiuchi, and Naoya Koizumi. 2021. PicPop: A pop-up picture book comprising mid-air images. In *CHI Conference on Human Factors in Computing Systems Extended Abstracts (CHI '21 Extended Abstracts), May 8–13, 2021, Yokohama, Japan.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3411763.3451539

1 INTRODUCTION

A pop-up picture book provides users with surprises and interaction with its characters by making illustrations in the picture book appear three-dimensional In general, the illustrations in pop-up picture books are made to pop out by inserting geometrically folded papers between the pages of the book and fixing them in place using an adhesive. However, it is difficult to incorporate a three-dimensional structure into a picture book, and the process requires considerable skill. Therefore, several interaction systems for implementation in pop-up picture books have been realized by superimposing digital information into picture books and illustrated books. Icebook [2] and Electronic Popables [6] are picture books that employ animations and lights, respectively. A system using a head-mounted display (HMD) facilitates the observation of three-dimensional images [1], but limits the number of observers.

In this study, we use a mid-air image to realize the visual impression that a digital image has popped out from a physical picture book. The mid-air image is a real image that is formed in the air via the reflection and refraction of the light emitted from the light source of the optical elements of the book. These mid-air images can be observed with the naked eye, and without the need of employing a special optical device such as an HMD or projecting the images onto a real object using a projector.

We employed a reflective mid-air image-display method, in which the mid-air image is formed via the reflection of light from the light source onto a glossy surface. The advantage of this method is that the background of the mid-air image is a glossy surface instead of a device, such as an optical element or a light source. Consequently, the user is not required to look into the mid-air imaging device, as it will be outside the center of their field of vision, which will increase the user's surprise and the factor of unexpectedness when the mid-air image pops out.

We present PicPop, which is a system in which the characters are made to pop out from a picture book via mid-air imaging, as shown in Figure 1. Using reflective paper as the mid-air image-display surface, the images can be displayed in the same manner as that used in conventional systems, and a highly flexible background that would be useful in picture books can thus be realized. The use of mid-air images allows picture-book designers to create pop-up books comprising static images as well as animations. In addition, by modifying the design of PortOn [4], we were able to reduce the size of the display device while maintaining the luminance of the mid-air image at the desired value. To facilitate the interaction of the user with the mid-air images of the book, sensors are built into the book to change the scene when the observer turns the page.

Fig. 1. PicPop showing a mid-air image.

2 RELATED WORKS

2.1 Interactive book

Icebook [2] and SequenceBook [8] are examples of systems that use projectors to extend the functions of picture books; however, they do not make images pop out of the books. In contrast, MagicBook[1] displays three-dimensional models that match the content of the illustrated books and stories; however, it requires the user to wear an HMD.

It is difficult to physically create a structure that makes illustrations pop out from the book; furthermore, experiences that require special equipment limit the number of people who can experience them. Therefore, to create a pop-up picture book that does not require advanced design techniques, a mid-air image is used in the proposed system.

2.2 Mid-air image

Optical elements that can easily display mid-air images are commercially available, and several types of interactions using these elements have been proposed. In MARIO proposed by Kim et al. [3], the interaction between a real object and mid-air image is realized using a depth sensor with Kinect. In this system, a mid-air image character can be presented jumping to real building blocks by measuring its highest point. Takazaki et al. used Kinect and Leap Motion to realize the user's interaction with a mid-air image by tracking the user's hand movement [7]. In addition, They projected images that were shielded by the user's hand onto it. However, the combination of the image-projection system with hand-tracking technology requires familiarity with the operation of sensors. Therefore, we adopted an interaction design that connects the manipulation of the mid-air image with the movement of physical entities, such as that in the case of MARIO, instead of using a gestural input.

There are various types of mid-air imaging optics, but we chose a method that allows the user to focus on the displayed image and the location at which the image is displayed, such as a picture book, rather than on the mid-air imaging device. EnchanTable [9] and PortOn [4] are examples of research conducted on the display of such mid-air images. EnchanTable is a mid-air imaging device that can be applied to common tables. However, the display needs to be placed at the bottom of the display surface, which increases the size of the device. In the case of PortOn, this problem is solved using a mirror inside the device to place the display above the display surface, thus realizing a portable mid-air imaging device.

Placing our device and picture book on a table can provide the users with a magical experience. We also intended to reduce the depth of the device because the space available for placing the device and picture book was small. Therefore, on referring to the work of Osato et al.[5], we tilted the mirror inside the device and adjusted the display position to reduce the size of the device, without changing the position at which the mid-air image was displayed.

3 PICPOP

The orthogonal micro-mirror structure comprises an optical system that displays a mid-air image. It forms a mid-air image at a position symmetrical to the position of the light source with respect to this optical element. These are referred to as micro-mirror array plates (MMAPs).

A viewing control film was used to eliminate unwanted light that degraded the visibility of the mid-air image. The light transmitted through the MMAPs was eliminated by the viewing control film in front of the MMAPs. The light directly incident on the MMAPs was also eliminated by the viewing control film in front of the display.

The system design of PicPop is presented on the left in Figure 2. We designed the system based on PortOn's design; moreover, to realize the system, we placed the PicPop device and picture book on the desk.

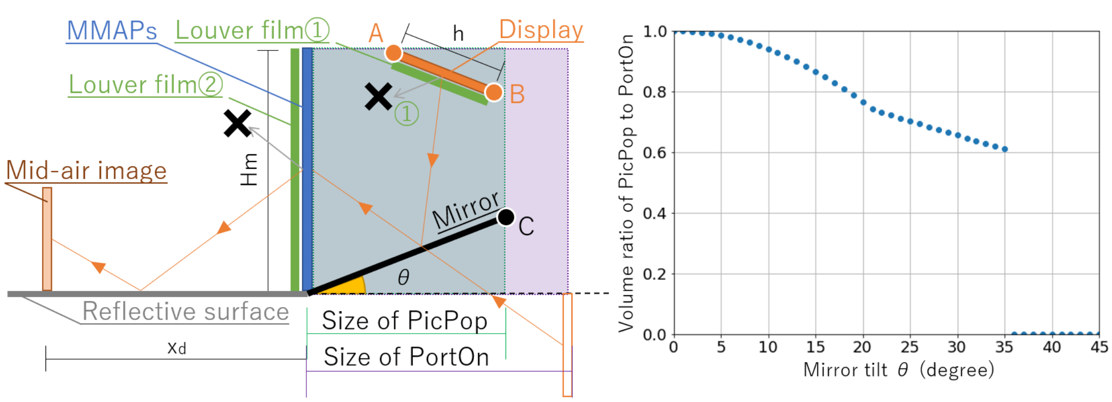

Fig. 2. Design of PicPop and device volume at 200 mm distance between mid-air image and MMAPs.

However, in the case of PortOn, if the position at which the mid-air image is displayed is moved away from the optical element, the depth of the device must be increased by the same amount, thereby reducing the space for the device and books on the desk. To solve this problem, we reduced the depth of the device by tilting the mirror inside the device and adjusting the position of the display without changing the position of the mid-air image.

The ratio of the device volume of PicPop to PortOn can be calculated using equation (1). First, we need to determine the coordinates of the light source of PicPop to calculate its volume. Let the distance between the mid-air image and MMAPs be x_d, the length of the display as the light source be h, and the height of the MMAPs be H_m. If the front end point of the display is A(A_x, A_y), the back end point is B(B_x, B_y), and the front end point of the mirror is C(C_x, C_y), then A, B, and C can be expressed as follows:

$$A_y = hcos2\theta + x_d sin2\theta,\ B_x = x_d cos2\theta,\ C_x = \frac{x_d H_m}{H_m + x_d tan\theta}.$$

Based on these formulas, the ratio of the volume of PortOn to that of PicPop becomes

$$\text{Volume ratio} \quad = \quad (max(A_y, H_m)) \times \frac{max(B_x, C_x)}{H_m \times x_d}. \tag{1}$$

The plots based on this formula are presented to the right in Figure 2. As the mirror was mounted at a 20° angle, the volume was reduced by approximately 80% than that in PortOn.

To display the mid-air image on a picture book, the book surface must have reflective properties. We confirmed the quality of the mid-air images that were displayed on a commercially available glossy paper surface. The luminance of the mid-air image was measured when each paper was used as reflective material. Furthermore, we compared the sharpness of the outline of the mid-air image visually. Figure 3 presents the results for each study. Consequently, Canon Photo Paper, Glossy Pro PT-201A420, was used because it presented the brightest and clearest image.

We used a sensor to determine whether the page has been turned and to change the scene. The microcomputer (ESP32) detects the page feed with the circuit of photoreflector (LBR-127HLD) , and sends this to the computer via serial communication. The computer changes the image based on the page feed signal, and sends the image that matches the page of the picture book to the light-source display of the mid-air imaging system.

4 LUMINANCE EVALUATION

We measured and compared the luminance of the mid-air images displayed by PortOn and PicPop. Luminance meters were placed to the left as shown in Figure 4, and the luminance of the mid-air images was measured for each device. The mid-air image was displayed at a distance of 200 mm from the MMAPs, and the luminance meter was pointed at the center of the image. The mid-air image and luminance meter were separated by 1000 mm, and the luminance was measured while changing ϕ from 20° to 40°. An acrylic mirror was used as the display surface for the mid-air images, and the room used was dark. Five measurements were obtained at each angle, and the average value was used as the luminance at that angle.

The view control film of Shin-Etsu Polymer Co., Ltd. was used as a louver film to block specific light that would otherwise result in an undesired image. The maximum transmission angle was 25°, and the view angles were 48° and 60° . In the case of PortOn, the louver film was placed only in front of MMAPs; in the case of PicPop, the film was placed in front of both the MMAPs and display. In the following, the combination of the louver film used in PicPop is

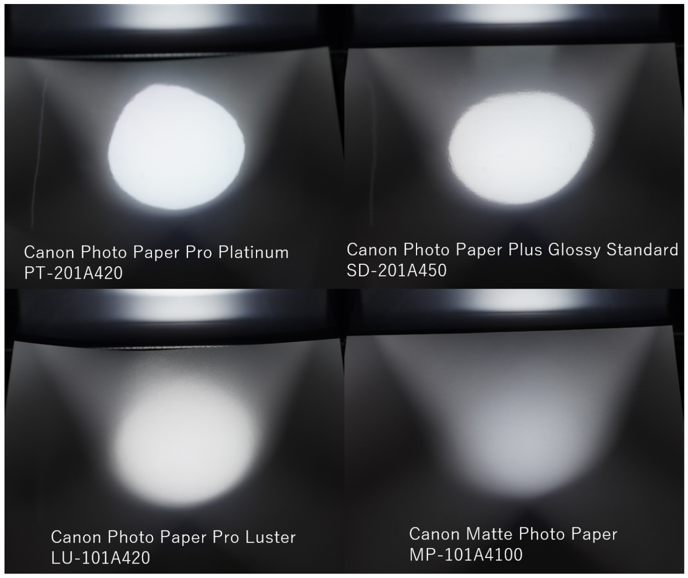

Fig. 3. Mid-air image obtained when each paper is used as a reflective element.

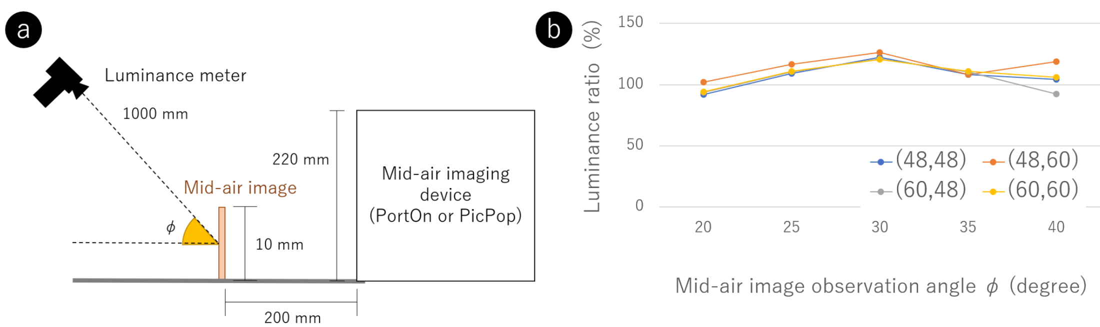

Fig. 4. Luminance evaluation. a:Evaluation conditions, b:Brightness comparison between PortOn and PicPop.

denoted as θ_{MMAPs}, $\theta_{display}$), where θ_{MMAPs} is the view angle of the louver film placed in front of the MMAPs, and $\theta_{display}$ is the view angle of the louver film placed in front of the display.

The results of the experiment are presented to the right in Figure 4. The vertical axis represents the luminance ratio of PicPop to that of PortOn when the louver film in front of the MMAPs is the same, and the horizontal axis represents the angle at which the mid-air image is observed. When the angle is 30°, the luminance of PicPop increases to approximately 120% that of PortOn.

From the experimental results, it was confirmed that the luminance reduction caused by the polarizer was improved depending on the value of ϕ. In particular, when the angle was 30°, the luminance was improved by up to 126%. When the angle was 20° or 40°, the luminance of the light in that direction was significantly attenuated, owing to the characteristics of the louver film; thus, the luminance was considered to be lower than that of PortOn.

5 INSTALLATION

Using PicPop, we created a pop-up picture book of Cinderella. Figure 1 presents this example. When a mid-air image is displayed by projecting an illustration onto paper, it is significantly affected by the reflection characteristics of each color from the paper. As it was confirmed that some of the images were blurred, we used silhouettes to display the mid-air image.

6 CONCLUSION

In this paper, we presented PicPop, a pop-up picture book that uses mid-air images. By adjusting the inclination of the mirror in the system, we were able to reduce the size of the system and make it easy to place on a table with a picture book. By using paper with reflective properties for the picture book, we were able to display mid-air images on the picture book while maintaining the ease of handling the book that only paper can provide.

We compared the luminance of PortOn and PicPop and confirmed that the luminance can be significantly improved depending on the angle of observation. In particular, when observing a mid-air image at a tilt of 30°, the maximum luminance of PicPop was found to be 26% greater than that of PortOn.

It was found that the color of the illustrations printed on paper and the distortion of the paper affected the display of the mid-air images. As a future prospect, we intend to identify a color tone that makes the mid-air image easy to observe, and investigate how to suppress the distortion of the mid-air image. In addition, we intend to create a picture book based on these findings.

ACKNOWLEDGMENTS

This work was supported by the JSPS KAKENHI Grant Number JP20H04223.

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