Coming to the University of Memphis from Pittsburgh, Pennsylvania, Ethan Costello is a double major student in the Department of Electrical and Computer Engineering at the Herff College of Engineering since Fall 2019. In conjunction with his double major, he is a student in the Helen Hardin Honors College. Ethan is expected to graduate in Spring 2023. He has been working as a research assistant in the Optical Imaging Research Laboratory with Dr. Ana Doblas. During his time in the lab, he discovered more about his research interests in imaging and sensing. Ethan is also planning to work with Dr. Eddie Jacobs to become more exposed to complicated sensors and sensor processing. After graduating, Ethan plans to pursue graduate school in electrical engineering.

This paper received a QuaesitUM outstanding paper award.

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Two-Way Pepper Ghost Tunnel: Theory, Design and Analysis

Faculty Sponsor

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Abstract

Three-dimensional (3D) displays allow users to experience 2D images/videos in-depth illusions. Among the different 3D displays, we can distinguish the Pepper ghost illusion, which is a common approach to create a 3D hologram without goggles. In this work, we have upgraded the conventional Pepper ghost illusion, named as the two-way Pepper ghost tunnel, to create two simultaneous holograms. Contrary to the conventional Pepper ghost, the Pepper ghost tunnel requires two liquid crystal displays (LCDs), which are controlled by the same Arduino, to illuminate a 45-deg transparency sheet in both directions, allowing two different holograms to be viewed from each side of the tunnel. We have described a practical procedure for building the apparatus and validate its performance. Due to the simplicity of the apparatus, the Pepper Ghost tunnel allows undergraduate students to increase their knowledge in geometrical Optics and its integration with electrical circuits.

Introduction

Holography is an imaging technique that creates an optical illusion to transform two-dimensional (2D) images into 3D perspective. For example, one of the most famous holographic examples within media entertainment is the fictional hologram of Princess Leia from the Star Wars saga. 3D free-standing holograms like Princess Leia's hologram are still costly methods with contemporary's technology, reducing its applicability. The majority of low-cost methods of generating 3D illusions from 2D images used simple concepts of Optics. For example, anaglyph glasses are based on the stereoscopic 3D effect, color encoding two laterally shifted images of the same scene [1, 2]. In other words, anaglyph 3D images are composed of two differently colored images (e.g., red versus cyan) in which each of these images is only perceived by an eye. The 3D images are created by our visual cortex of the brain which realizes that both images are from the same scene and composes them into a 3D scene [3]. The principle of combining two laterally shifted images is also used in the polarizing goggles in which the color filters have been replaced by circular polarizers [4, 5]. Whereas monochrome 3D scenes are created using anaglyph glasses, the polarizing goggles generate full-color 3D scenes.

The use of stereoscopic-based goggles may lead to some user's discomfort such as mild migraines. The Pepper Ghost technique is an approach to create 3D illusions but without using goggles [6], being more user-friendly compared to the polarizing goggles. The Pepper Ghost technique is based on Snell's law [7] in which 2D images are reflected using a transparent sheet set at a 45-deg angle (Figure 1). Only users located in one side of the transparent sheet can observe the hologram. In this work, the traditional Pepper Ghost method has been upgraded to include an extra LCD to illuminate the transparency sheet from above, creating two distinct holograms that can be viewed individually from both sides of the tunnel. This preliminary work will enhance the 3D hologram experiences in media entertainment and gaming venues.

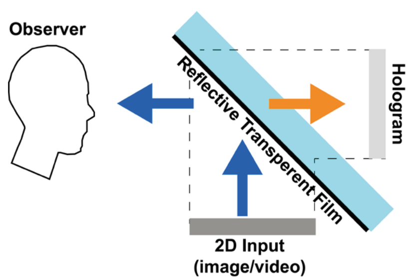

Figure 1. Illustration of the traditional Pepper Ghost method to create holographic images (e.g., hologram) from 2D images based on Snell's law.

Theory of the Two-Way Pepper Ghost Tunnel

The traditional Pepper Ghost hologram (Figure 1) uses the optical principle of Snell's laws [7]. These laws describe the phenomenon of reflection and refraction of light propagating within different uniform media, such as water, glass, or air. In particular, these laws are mathematical formulas to estimate the angles of refraction and reflection based on the angle of incidence. Figure 2 illustrates both phenomena such as refraction and reflection. The Snell's laws are used to ray tracing the optical path knowing the angle of incidence or refraction as well as to estimate the refractive index of a material. It is important to mention that the refraction index of a material is an unitless optical parameter that compares the speed of light traveling through the material and vacuum (e.g., air). These laws state that: (1) the angle of refraction is directly related to the incident angle (see Figure 2a), and (2) the angle of reflection is equal to the incident angle of the light (see Figure 2b). The refraction law states that the ratio of the sines of the angles of incidence (θ_1) and refraction (θ_2) is equivalent to the reciprocal of the ratio of the indices of refraction. In other words:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}.$$

The refraction law is also satisfied in meta-materials, which allow light to be bent backward at a negative angle of refraction with a negative refractive index. The Pepper Ghost effect is related to the backward refraction law, which is the refraction law [7] in the opposite direction. This means that a transparency sheet set at an angle of 45-degree can create a perfect replica of the image displayed on an LCD, creating the illusion of an image floating in the air. Note that, actuality, the image has been only refracted off by the transparency sheet. The use of a 45-deg transparency sheet ensures that the size of the holographic images coincides with the size of the projected imaged onto the LCD. Other angles could lead to an optical magnification or demagnification.

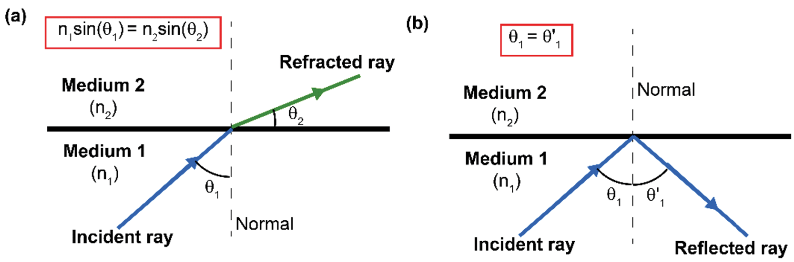

Figure 2. Illustration of the Snell's law: (a) refraction and (b) reflection.

In the design of the tunnel, an additional LCD that is located above the transparency sheet has been added (Figure 3). Since two LCDs are used, the transparency sheet creates two holograms. However, these holograms appear only in one side of the Pepper Ghost device since the transparency sheet refracts the image in different direction depending on which the location of the LCD. In other words, the bottom LCD (named as LCD 1 in Figure 3) refracts the image at a 45-degree angle to the right and reflects it at a 45-degree angle to the left, enabling the observation of the hologram in the left-side of the display. Consequently, the hologram created by the top LCD (e.g., LCD 2 in Figure 3) is only observed from the right-side of the display. Therefore, the use of two opposed LCDs in a traditional Pepper Ghost configuration generates two separate holograms, enabling their distinct observation from the two sides of the device (e.g., creation of a tunnel effect).

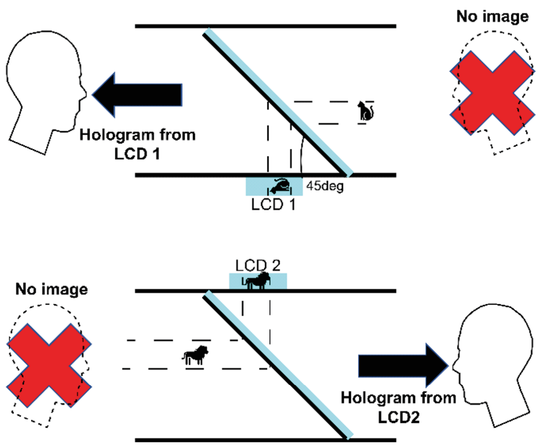

Figure 3. Illustration of the proposed Pepper Ghost tunnel. The observation of each generated hologram occurs in different side of the display (e.g., the hologram displayed by LCD1 and LCD2 is observed from the left-, and right-side of the display, respectively).

Design of the Two-Way Pepper Ghost Tunnel

This section focuses on the description of the design of the prototype of the Pepper Ghost Tunnel (Figure 4). To do this, we have used two liquid crystal displays (LCDs, product item 1480, Adafruit) that are controlled by the same Arduino board (ELEGOO UNO R3). This board is powered by two AA batteries to DC power supplies. The LCDS and the board are connected using a single breadboard and various breadboard jumper wires. Since the Arduino board that we have used for this project does not have enough pins to control more than one LCD at a time, both LCD display the same sequence of images, generating the same hologram. To create a stable connection to the displays and avoid any loss of images, we have soldered the wires directly to their inputs/outputs. All the electrical components are properly enclosed in blackened cardboard for security reasons.

This experiment could be design as a STEM kit to introduce kids to Optical Engineering, through the hands-on experience of building their first holographic display. The total cost of the material for the Pepper Ghost tunnel sums to approximately $106, the two LCDs being the most expensive parts (2 x $24.95 = $49.90, which is nearly 47% of the total). The transparency sheet used is a regular low-cost transparency film for inkjet printers. This price can be lowered by buying cheaper LCDs, which may lead to worse image quality. Another approach to reduce the cost involves the purchase large volumes of components. For example, the same LCDs could cost 25% if we purchase more than 100 displays. The cost of STEM kits varies from $20-$150. Therefore, a significant reduction in the project cost is necessary to develop a commercial STEM kit.

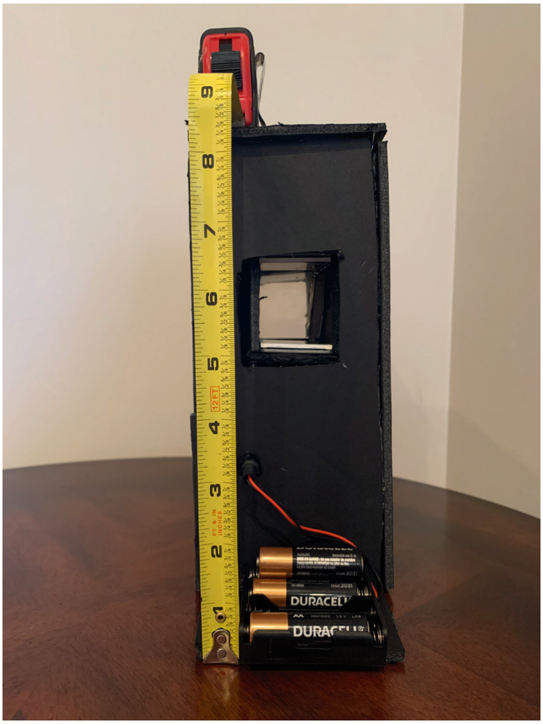

Figure 4. Experimental prototype of the Pepper Ghost Tunnel using cardboard to enclose the transparency film and the two opposed LCDs. The total size of the prototype is 101.6×241.3×190.5mm (Width×Height×Depth).

Experimental Validation

For the sake of simplicity and to prove the concept, the programming used in our model is the default LCD testing script provided by Adafruit. This script runs through a series of images, text, and video that are created using lines, circles, and triangles to test each pixel of the display. During the design of the prototype, this script has helped us to realize that the displays were disconnecting since they were not displaying the full length of the test images, allowing us to take the decision that soldering of the wires was needed.

This testing script was also used to confirm that the LCDs connected in series could display synchronized video. Therefore, this basic code allowed us to test the electrical components as well as to validate our design concept to upgrade the traditional Pepper Ghost illusion into the proposed Pepper Ghost tunnel. Figure 5 shows the experimental validation of the tunnel effect of the proposed device. This figure illustrates a selected set of displayed images on the LCDs (first column) and the pictures of the generated holograms from each side of the tunnel (second and third column). These images prove that it is possible to view images from both sides of the tunnel without the interference of the other side's hologram.

One can also notice that there is a slight distortion in the hologram images when compared to their originals. In particular, this distortion is more noticeable in the hologram generated by the top LCD. This distortion may be caused by a combination of experimental misalignments between the position of the top LCD and the transparency sheet. Another problem of this prototype is that the holograms are distorted by a severe glaring effect coming from the LCDs, reducing the image contrast of the holograms. A future prototype would involve the design of the device using a 3D-printing house, improving the alignment of the components.

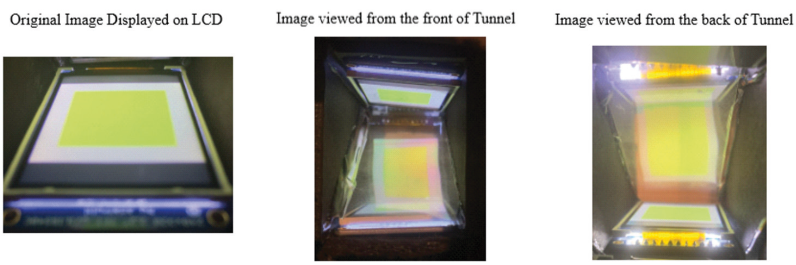

Figure 5. Experimental validation of the proposed Pepper Ghost Tunnel. The first column shows the images displayed on LCDs. The second column illustrates the hologram generated by LCD1 and observed in the left-side of the display. The third column shows the hologram generated by LCD2 and observed in the right-side of the display.

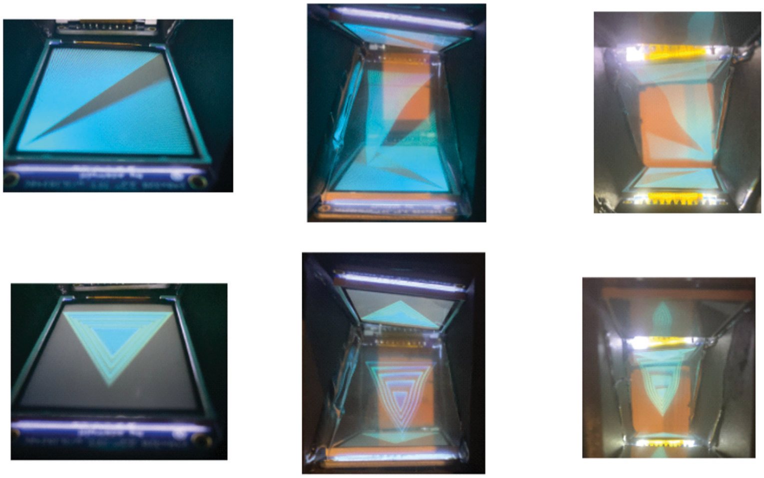

Figure 5. continued.

Discussion and Conclusion

In this work, the traditional Pepper Ghost illusion has been upgraded to create a tunnel effect by introducing an additional LCD. The working principle of the Pepper Ghost tunnel is that both LCDs should illuminate the transparency film in opposed direction, generating distinction holograms in each side of the device. Since we have used a single Arduino to control both LCDs, the two generated holograms display the same image with a reflection along the vertical direction. The performance of the experimental prototype has been evaluated with a sequence of basic images, demonstrating successfully how to expand the idea of the single-view Pepper Ghost illusion to a pair of holograms viewed from each side of a tunnel. The features (size and resolution) of the holographic displays depends on the LCDs used. For example, the size of the holographic image depends on the number of pixels on our LCDs.

The resolution of the holographic images is defined by the minimum separation between two distinguished image features. Experimentally the resolution can be determined by displaying a sinusoidal pattern whose frequency increases and estimating the maximum spatial frequency that we can display. The maximum spatial frequency is the inverse of the minimum spatial period of the sinusoidal pattern. Following the Nyquist sampling theorem, the minimum spatial period of a sinusoid is 3 pixels. Based on the manufacturer's information, the pixel size of our LCDs is 18.67 μm, resulting in a spatial resolution of 56.01 μm. Whereas this is the strict definition of the resolution in the holographic image, it is important to mention that the perceived resolution also depends on the pixel depth of the LCDs. In other words, a perceived color is related to a given intensity values. Whereas an 8-bit LCD only provides 256 different colors to display an intensity value, an 18-bit LCD enables a more accurate representation of intensity values (up to $2^{18} = 262,144$), displaying images with a higher contrast (e.g., difference between the maximum and minimum intensity values). Therefore, the perceived resolution is highly dependent on the based on the pixel depth of the LCDs.

Theoretically, the physical and perceived resolution should not be affected using colored LCDs instead of monochrome ones. One of the major problems of the prototype is the presence of a high intense glare, reducing the contrast of the generated holograms. This glare effect can be reduced by using a better transparency sheet or introducing a single or a combination of linear polarizers set at a specific angle to reduce the amount of glared light. Further improvements of the current prototype also may involve the design of a 3D- printed housing for the electronics, the screens, and the transparency sheets, which would improve the setting of the transparency sheet at 45 degrees by sliding it into a predetermined slot. It would also allow us to replace the sheet in case of breakage or for cleaning purposes. In addition, the design of the 3D-printed cage would allow us to insert the LCDs, hiding them with indentation, reducing the glare problem.

Having a 3D-printed housing would further help us to create a darker environment, improving the contrast of the generated holograms and enhancing the experience of the optical illusion. It may also be possible to enhance the resolution of our system by finding an improved LCD, however we believe that we have found the most cost-efficient option in terms of quality and price of an LCD. Although there are other devices to create holographic displays, only the reflective prism-based Pepper Ghost device [8] and the Pepper Cone [9] provide a similar effect as our Pepper Ghost Tunnel. The reflective prism-based Pepper Ghost device relies on the 2D projection of four images onto the sides of a prism.

The main limitation of such device is the size of the images, since the area of a display must be separated into 4 regions, generating images with reduced size. In contrast, the Pepper Cone only requires a single image. To generate 3D holographic images without any distortion, it is necessary an extensive calibration of the system. Note that such calibration is not required in our device. The main problem of these two versions of the Pepper Ghost is that they do not generate 3D images with real parallax. Parallax is the perceived effect when the distance between two 3D objects changes when we move our heads. The proposed Pepper Ghost Tunnel can potentially be improved by inserting additional transparency sheets in tandem with their corresponding pair of LCDS, leading to the first 3D parallax Pepper Ghost Tunnel.

This project is under development and has been submitted to the upcoming Imaging and Applied Optics Congress host by OSA. We envision that such Pepper Ghost Tunnel could be widely use in museums to display simultaneous 3D holograms. In addition, the integration of such system with audio and interactive screens would enhance the 3D experience for visitors. Another potential application of such system is in gaming venues as potential gaming monitors.

Acknowledgements

Doblas acknowledges the support from the National Science Foundation (NSF, # 2042563), the University of Memphis, UMRF Ventures, and the Herff College of Engineering.

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