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Scalable Autostereoscopic Display with Temporal Division Method

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Abstract

Science-fiction has frequently depicted people directly interacting with life-size autostereoscopic images projected from the walls of buildings in public places. In this paper, we present a large modularized autostereoscopic display. The shape and size can be easily changed by rearranging the number of the multiple display modules. We propose a reconfigurable temporal division multiplexed autostereoscopic display module that can display aerial images. Moreover, we show that the temporal division multiplexing method allows the autostereoscopic display to be viewed from a broad range of positions. In this paper, we discuss the design and implementation of this modularized 3D display technology. Furthermore, user evaluations confirmed that the depth perception of the image was improved by connecting the multiple display modules.

CCS Concepts

• ***Human-centered computing*** → ***Displays and imagers;*** • ***Computing methodologies*** → *Mixed / augmented reality;*

1. Introduction

3D displays have been gaining recent attention, with many such technologies introduced in movies, home TVs, PC monitors, games, and other areas. However, such 3D display technologies are rarely seen in public places, such as the walls of buildings or showcases in shops. So far, there is no established standard method to introduce these displays into public spaces. Currently, 2D displays solve this issue by adopting a tiling method that offers scalability and allows the displays to fit into large public display spaces, such as walls and billboards.

In this study, we explore the construction of a modularized autostereoscopic display that offers scalability and can fit into large public display spaces. Autostereoscopic displays construct aerial or floating images that allows the user to view these images in a 3D form without using specialized glasses or headgear, making it an ideal solution for public spaces. However, such a single large autostereoscopic display is difficult to transport and must be redesigned for different places. Therefore, this method increases the initial production costs and has low flexibility. Recent research in autostereoscopic displays has focused on implementing scalable displays [DAA*11] [LIK*05] [LWZ*13] [TTH14]. This research was been based on integral imaging techniques or on a combination of a transparent narrow scattering profile screen and multiple projectors. As such, these autostereoscopic displays are constructed with the spatial division method [Bal06] [Ive03] [JUN*15] [MP04]. In the spatial division method, the attempt to produce smooth motion parallax and wide viewing angle results in reduced resolution. Therefore, the spatial division method incurs a trade-off between the resolution of the displayed image and the number of viewpoints. As implemented in [SMG*05], the issue can be avoided by placing the spatial division autostereoscopic display modules in a circular arrangement. Although this method secures the viewing angle of the user, it restricts the viewing area for the user and their movement. Moreover, as suggested in [TTH14], this issue can be addressed by lens shifting or aperture shifting. However, since each module only has a single purpose in this method, the initial costs by cannot be reduced by mass-producing a multi-purpose module, which is one of the merits of the module method.

In this research, we propose a temporal division method for an autostereoscopic display module which can display a floating image in air. We expect that a wide viewing angle can be realized without compromising the image resolution by constructing a display module that uses a temporal division multiplexing method. In addition, we show that enlarging the screen size horizontally by tiling multiple display modules is the first step towards realizing our concept. Since both human eyes are aligned in the horizontal direction, autostereoscopic displays require accurate light ray control in the horizontal direction rather than in the vertical direction. Therefore, if scalability in the horizontal direction can be achieved, there is a possibility of scalability in the vertical direction as well. Thus, we propose a temporal division autostereoscopic display module with a horizontally enlarged screen size as the first step to realize our concept. Moreover, we implement two such autostereoscopic displays horizontally and evaluate binocular disparity in the displayed image astride on two display modules.

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The main contributions of this paper are:

- Introduction of a scalable autostereoscopic display using a temporal division multiplexing method
- Prototype implementation and verification of binocular disparity displayed image astride on two display modules

2. Related research

2.1. Autostereoscopic display

Recently, much research on 3D displays has focused on autostereoscopic displays. Most of such research has utilized spatial division multiplexing [Bal06] [Ive03] [JUN*15] [MP04] as a common representative technique to build autostereoscopic displays. However, spatial division multiplexing has a trade-off between image resolution and the number of viewpoints. Therefore, the image resolution decreases as the number of viewpoints is increased in order to widen the field of view. Temporal division multiplexing [JMY*07] [MTLC92] was proposed to solve this trade-off between the number of viewpoints and image resolution. In addition, the parallax barrier method [IYS93] was proposed as another representative method for autostereoscopic display research. Regarding the parallax barrier method, it was proposed in prior publications [LNL*06] [PPK00] that the resolution reduction could be suppressed by combining spatial division multiplexing and temporal division multiplexing, or by barrier optimization corresponding to contents [LHKR10]. Although these studies demonstrated the display of autostereoscopic images, the images were generated near the display surface. Thus, depth perception depends not only on binocular disparity and motion parallax but also on accommodation (eye focus adjustment). In particular, the dependence of accommodation on depth perception cues increases when the users see a nearby object. Therefore, when the user interacts directly with autostereoscopic images displayed near a display surface, inconsistent accommodation occurs between the autostereoscopic images and the real object, leading the user to feel that the images and the real objects exist in different places. As such, in our research, we focus on displaying an autostereoscopic image in the air in order to facilitate direct interaction between autostereoscopic images with real objects.

2.2. Floating image displays

There are many methods that can be used to display aerial images in order to realize direct interaction between real objects and images, or to attract attention as advertisements. The representative methods for generating aerial images include using lenses [MHKL05] [Yos11] [YSK*11], a concave mirror [BHI*11], and a beam splitter [BR06] [HBCdlR11] [HKI*12] [LLS17]. In recent years, a method [KKN16] [MHF*14] using an orthogonal micro mirror array such as ASKA3D instead of a beam splitter was also proposed. In addition, a light field reproduction method involving stacking multiple printed films [LWH*11] or by stacking planar LCD panels [WLHR11] [WLHR12] were proposed. These are autostereoscopic displays, which can display aerial images using spatial division multiplexing. On the other hand, a method for realizing an autostereoscopic display using temporal division multiplexing [Kak07] [NZY*12] [SSR11] was proposed. Although this method can be used to display aerial autostereoscopic images, the system consists of just one unit and does not consider enlarging the screen size using multiple tiled displays. Thus, we focus primarily on enlarging the screen size using multile tiled display modules.

2.3. Scalable displays

The famous CAVE VR system [CNSD93] was constructed as a 3D display with a large immersive feeling using rear projection from the four walls of a room. [SMG*05] is constructed as a large autostereoscopic display by tiling multiple small autostereoscopic display modules using the parallax barrier method. While this research focused on tiling using stereoscopic display modules, the stereoscopic images were not projected in the air. The closest matching research we could identify uses a large autostereoscopic display constructed by tiling multiple autostereoscopic display modules [DAA*11] [LIK*05] [LWZ*13] [TTH14]. Although these studies demonstrated methods for displaying autostereoscopic images in the air, and the systems can be constructed as one large autostereoscopic display by tiling small display modules, these display modules were designed to use spatial division multiplexing. The primary differentiating point is that our research focuses on a tiling method for display modules designed to use temporal division multiplexing. We expect that using a display module design to use temporal division multiplexing will make it easy to enlarge the screen size and viewable position without the trade-off between image resolution and viewing angle. An autostereoscopic display was previously constructed [UIS*14] by tiling multiple autostereoscopic display modules, where the modules were designed to use temporal division multiplexing. However, this research focuses on widening the viewing angle and increasing the number of simultaneous users, rather than focusing on enlarging the screen size.

3. Scalable autostereoscopic display

3.1. Principle of scalable autostereoscopic display

In this section, we describe the requirements for designing a temporal division multiplexed autostereoscopic display module, which can be used to project autostereoscopic images in air and enlarge the screen size by tiling. Here, enlarging the screen size refers to displaying autostereoscopic images larger than one display module by tiling multiple display modules. This requires that the displayed autostereoscopic images have the following properties:

1. Seamless connection among images astride on multiple display modules
   a. No spatial gap between images on multiple display modules
   b. No spatial displacement between images on multiple display modules
2. Displaying autostereoscopic images that are larger than a single display module size
   a. Displaying autostereoscopic images to the display edge, even if user sees an image from an oblique viewpoint
   b. Displaying autostereoscopic images free from distortion and aberrations, even if user sees an image from an oblique viewpoint

The seamless connection among autostereoscopic images astride on multiple display modules is further divided into two requirements:

Satisfying 1.a requires a bezel-free display module. Therefore, in this research, we cover the entire display surface with optical elements to construct bezel-free display modules. Satisfying 1.b requires displaying distortion free floating images. This requires the system correct distortion and aberrations in the image, or it requires designing the system such that the system can display distortion-free autostereoscopic images. In this paper, we construct an autostereoscopic display that uses reflecting optical elements like mirrors, rather than refracting optical elements like lenses.

Next, since 2.a is equivalent to 1.a, the aforementioned solution to 1.a also solves 2.a. In order to conform to requirement 2.b, the display module must be constructed as a wide viewing angle display. We discussed many methods for constructing autostereoscopic displays in the previous section. However, spatial division multiplexing requires a trade-off between image resolution and the number of viewing points. Thus, we realize this wide viewing angle display module by constructing an autostereoscopic display module using temporal division multiplexing. To summarize the above points, in order to satisfy the two requirements and display large autostereoscopic images exceeding one display module size, we design the autostereoscopic display modules according to the following design policies: a) constructing the entire display surface with optical elements, b) constructing a reflecting autostereoscopic display, and c) constructing the display modules to use temporal division multiplexing.

3.2. System description

The system consists of a motion tracking system, a micro mirror array, a transparent LCD, and a light source (Figure 1). The micro mirror array is an optical element which can converge light emitted from a certain spatial point to a symmetric conjugate point. When the light emitted from the light source passes through the transparent LCD and converges to a conjugate point, the user will be able to see the floating image on their eyes (Figure1(Top)). We used a motion tracking system to acquire and calculate the position of the user's eye. Once the eye position is tracked, light is emitted from the light source towards the user's eye, and the viewing frustum of the image displayed on the transparent LCD is calculated and displayed. As a result, the image displayed by the transparent LCD is projected in air and only enters one of the user's eyes. Thereafter, the image is calculated and projected for others' eyes. This system can show autostereoscopic images in air by switching and displaying these processed images at high speed. The position of the light source can be calculated using the following equation:

$$x_1 = \frac{x_e - A_1 y_e + d_2}{A_1} \tag{1}$$

$$x_2 = \frac{x_e - A_2 y_e + d_2}{A_2} \tag{2}$$

$$A_1 = \frac{y_{m1} - x_e}{x_{m1} - y_e} \tag{3}$$

$$A_2 = \frac{y_{m2} - x_e}{x_{m2} - y_e} \tag{4}$$

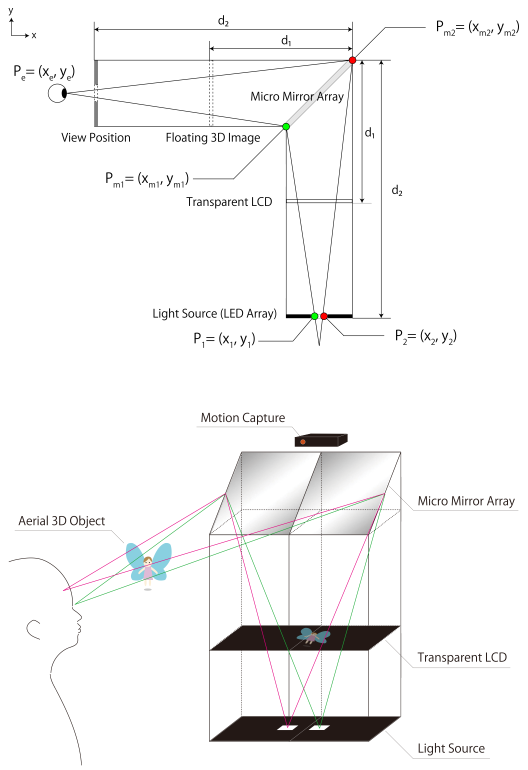

Figure 1: *(Top) Geometry of an autostereoscopic display. (Bottom) Enlarging the screen size by tiling two display modules.*

3.3. Image processing

Image processing (Figure 2) with this proposed system begins by detecting and calculating the user's eye's position to calculate the image to be displayed on the transparent LCD and the light emitted from light source. Based on the detected and calculated user's eye position, the image to be displayed and light are determined for a single eye. For example, an image and light for the right eye are determined first, then an image and light for the left eye are determined. Here, the calculations are divided into two phases. During the first phase, the image that must be displayed on the transparent LCD and light are determined. In the second phase, black images are displayed on the transparent LCD and the light source are turned off to reduce cross-talk. Because the transparent LCD and the light source are turned on while sequentially scanning the screen, images for the right and left eyes may be drawn on the screen simultaneously. Image processing with the proposed method follows a total of five steps, as shown in Figure 2.

4. Implementation

Our prototype autostereoscopic display modules (Figure 3) consist of 4 components. One Microsoft Kinect is shared between two modules for motion capture and for calculating user's eye positions.

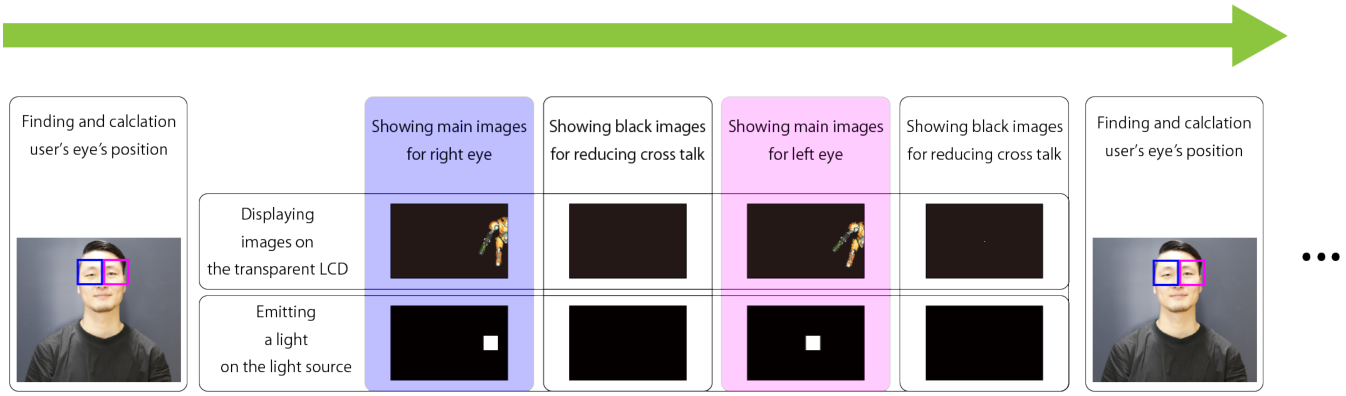

Figure 2: *Image processing flow.*

Figure 3: *(Top) A prototype module. (Bottom) Two adjacent prototype modules.*

One light source emits light based to the user's calculated eye position. The light source is a VG248QE display, which is a commercial product provided by ASUS. The transparent LCD is a decoupled LCD panel of an ASUS VG248QE display. A full HD light source and transparent LCD were used with a 120 Hz refresh rate. A 488 x 488 mm^2 micro mirror array (ASUKANET AIP-B488S05G) was used in the display system.

A displayed image astride on two autostereoscopic display modules tiled side by side is shown in Figure 4 In the current prototype implementation, the transparent LCDs and the light sources used in this prototype were larger than the micro mirror array, and they did not fit within the modules, so the position of the center of the displays were shifted. However, without above, the two modules are designed as same. Therefore, we expect that it is possible to connect these modules in a similar manner to extend to arrangements such as 1 x 3.

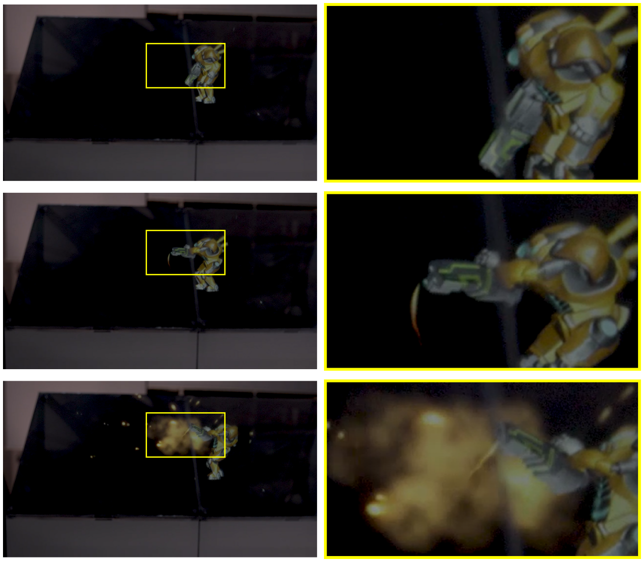

Figure 4: *A floating image displayed astride two prototype modules.*

5. Experiment

In this section, we investigated whether the proposed method can be used to enlarge the screen size by tiling. This refers to investigating if the user can perceive the image astride two modules as an autostereoscopic image. In other words, when displaying autostereoscopic images that astride two modules, the user should be able to perceive depth more accurately than when the images are displayed only on the edge of one module. In this experiment, two modules were placed side by side and used to display autostereoscopic images at various module locations. Then the participant evaluated the depth of the autostereoscopic image based on their perception. When the autostereoscopic image was displayed at the center of the display module, the participant can perceive the depth of the autostereoscopic image accurately because it can be viewed stereoscopically. However, when the autostereoscopic image astride two modules is displayed only at the edge of one module, one would expect that the accuracy declines compared to the case where an image is displayed at the center of the module. On the other hand, when two modules are adjacent and an autostereoscopic image is displayed astride two modules, it is expected that the participant can perceive the depth of the autostereoscopic image more accurately compared to displaying on one module. In this experiment, we demonstrate that the proposed method can be used to enlarge the screen size by tiling.

5.1. Experimental procedure

Two prototype display modules were placed adjacent, as shown in Figure 5 (Top). Each participant sat in a darkened room. The participant's head was stabilized with a chin rest, which was adjusted to align the center of the head with the center of the display module placed at the left side while facing the participant. In order to evaluate the effect of tiling under different conditions, the participants' eyes were aligned away from the center of the two display modules (Figure 5 (Bottom)). If the center of the eye of the participant is aligned with the center of the two displays, the edge of tiled display is close to the user's eye, while the edge of untiled display is far from the user's eye. Since those edges have different conditions the sole effect of tiling cannot be evaluated. Therefore, by aligning the center of the participant's eyes with the center of the left display module, the tiled display edge matches the condition in the untiled display edge. The center of the display module was placed 977 mm from the center of the head. As shown in Figure 5 (Bottom), a real object (15 x 2 x 2 mm^3) was placed 345 mm from the display module. The display modules displayed a 2 mm^3 cube as an autostereoscopic image. The participants answered whether the autostereoscopic image was in front or behind the real object. Participants were shown images from two display positions in the depth direction (10 mm and -10 mm from the real object) and five viewing angles (-12°, -6°, 0°, 6°, and 12°) leading to 10 data points for each participant. Each angle value was measured with respect to the center of the head and the horizontal direction. Each evaluation was repeated 5 times, for a total of 50 data points per participant. Furthermore, if the size of the autostereoscopic image changed as a function of the display position (since it becomes a depth perception cue), the size of the autostereoscopic image was controlled so that it did not change depending on the displaying position.

5.2. Experimental results

A total of 5 participant (3 male and 2 female) participated in this experiment. Participants had normal or corrected to normal vision. The experimental results are shown in Figure 6. Overall, responses from participants were 80% accurate, except for responses at -12° (58% accuracy). The -12° viewing angle indicates the module edge on the side where the display module is not expanded, and vice versa for the 12° viewing angle. There was no significant difference between the accuracy rate at 12° and 0°.

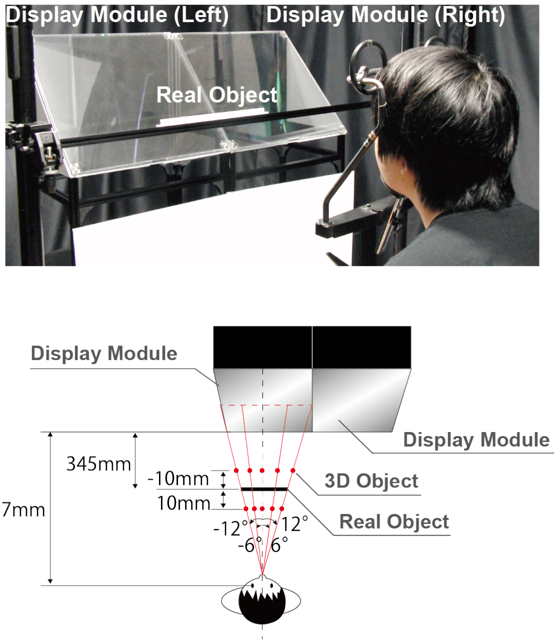

Figure 5: *(Top) Experimental environment. (Bottom) experimental conditions.*

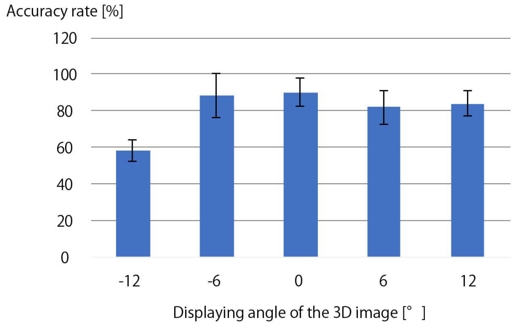

Figure 6: *Accuracy of depth perception for the autostereoscopic image in each display location.*

6. Discussion

6.1. Seamless connection

We found that a binocular disparity exists in the image displayed astride two connected display modules. This shows that the proposed display module is capable of showing seamless autostereoscopic images.

Most of the conventional temporal division multiplexing autostereoscopic displays use various optical elements, a transparent

LCD as a barrier, and an LCD. In contrast, our proposed method consists of optical elements, a transparent LCD, and a light source. Therefore, the proposed method can be used to remove one transparent LCD, thus the luminance can be improved compared to conventional systems.

6.2. Limitations

In this section, we discuss a few limitations of our approach. First, there is a limitation on the frame rate of the transparent LCD. It is 120 Hz at the maximum, and 4 frames per monocular a required in this proposed method. Therefore, if this prototype shows autostereoscopic images to one user, the image can be presented at 30 Hz, although the frame rate per person decreases as the number of users increases. We consider addressing this limitation using methods such as using a high frame rate display as a transparent LCD, and switching to a 2D display if the user is far away such that binocular disparity does not work effectively.

The next limitation regards the viewing angle of the micro mirror array. The viewing angle of micro mirror array used our prototype was $\pm 20^\circ$. Therefore, when the user is located close to the display module, the size of the displayed autostereoscopic images become small due to the limited viewing angle of the micro mirror array. However, as the user is further away from the display module, it is possible to show a larger autostereoscopic image.

Moreover, our prototype has aluminum frames for supporting a display module. Therefore, they cover and block the optical element, transparent LCD, and light source, which limits displaying images in a corner. We consider improving this limitation by constructing the frame with a transparent material or vibrating the display module itself at high speed to eliminate the non-displaying area with temporal division multiplexing.

Next, we describe the viewing range of this prototype. The viewing range is proportional to the size of the light source. The user can see the displayed images when the user views the display from the conjugate position or exists on the optical path of the light source. Therefore, the viewable range depends on the size of the light source and the viewable angle. If the user moves in the Z direction and the display modules have a wide viewing angle, crosstalk becomes significant because the diffusion angle is wide. Therefore, we consider addressing this limitation by moving the light source along the Z direction using linear motors or using a tomographic LED array according to the position of the user's eye.

The spatial gap between multiple modules occurs between the micro mirror array used as a display surface and between each component mounted on the display modules. Although the spatial gap between light sources can be solved by placing the density of the high luminance LED array, the spatial gap between transparent LCDs arises due the electric circuits required to operate the LCD and the glass for protecting the liquid crystal surface. Although it is possible to reduce the spatial gap by expanding the transparent LCD size using lenses, this method produces aberrations in the autostereoscopic images. However, the lens may cause image distortion and aberrations as the display size is increased. Therefore, we proposed a design to reduce the spatial gap using mirrors instead of lenses. A mirror was arranged to cover the area of the transparent LCD where it cannot display images (Figure 7). At this time, the mirrors are arranged to seamlessly connect to other mirrors on other display modules when multiple display modules are connected. As a result, since the image on the transparent LCD is reflected by the mirror, the image can also be displayed on the area of the transparent LCD where images cannot be displayed. Moreover, since the position of the conjugate viewpoint is also reflected by the mirror, the conjugate viewpoints differ between the image reflected by the mirror and the image displayed directly (Figure 7). Therefore, it is possible to display different images by multiplexing these images and lights temporally. However, the image reflected on the mirror is deformed, and thus the image is corrected using a homography transformation.

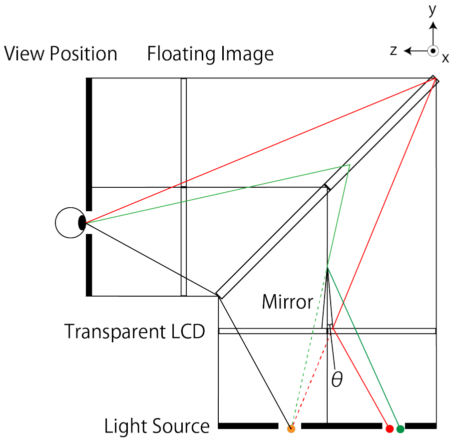

Figure 7: *A method for reduction spatial gap between transparent LCDs on astride multiple display modules.*

7. Conclusion

In this paper, we propose an autostereoscopic display module with temporal division multiplexing that can be used to construct large autostereoscopic displays by tiling multiple display modules horizontally. As a result of arranging two modules side by side, we confirmed experimentally that the user's depth perception improves by connecting the two display modules. In the future, we plan to enlarge the screen size horizontally and vertically in order to build a life-size autostereoscopic display.

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References

[Bal06] Balogh T.: The holovizio system. In *Proc.SPIE* (2006), vol. 6055. `doi:10.1117/12.650907`. 1, 2

[BHI*11] Butler A., Hilliges O., Izadi S., Hodges S., Molyneaux D., Kim D., Kong D.: Vermeer: Direct interaction with a 360° viewable 3d display. In *Proc. UIST '11* (New York, NY, USA, 2011), ACM, pp. 569–576. `doi:10.1145/2047196.2047271`. 2

[BR06] Bimber O., Raskar R.: Modern approaches to augmented reality. In *Proc. SIGGRAPH '06 Courses* (New York, NY, USA, 2006), SIGGRAPH '06, ACM. `doi:10.1145/1185657.1185796`. 2

[CNSD93] Cruz-Neira C., Sandin D. J., DeFanti T. A.: Surround-screen projection-based virtual reality: The design and implementation of the cave. In *Proc. SIGGRAPH '93* (New York, NY, USA, 1993), ACM, pp. 135–142. `doi:10.1145/166117.166134`. 2

[DAA*11] DeFanti T. A., Acevedo D., Ainsworth R. A., Brown M. D., Cutchin S., Dawe G., Doerr K.-U., Johnson A., Knox C., Kooima R., Kuester F., Leigh J., Long L., Otto P., Petrovic V., Ponto K., Prudhomme A., Rao R., Renambot L., Sandin D. J., Schulze J. P., Smarr L., Srinivasan M., Weber P., Wickham G.: The future of the cave. *Central European Journal of Engineering 1*, 1 (2011), 16–37. `doi:10.2478/s13531-010-0002-5`. 1, 2

[HBCdlR11] Hachet M., Bossavit B., Cohé A., de la Rivière J.-B.: Toucheo: Multitouch and stereo combined in a seamless workspace. In *Proc. UIST '11* (New York, NY, USA, 2011), ACM, pp. 587–592. `doi:10.1145/2047196.2047273`. 2

[HKI*12] Hilliges O., Kim D., Izadi S., Weiss M., Wilson A.: Holodesk: Direct 3d interactions with a situated see-through display. In *Proc. CHI '12* (New York, NY, USA, 2012), ACM, pp. 2421–2430. `doi:10.1145/2207676.2208405`. 2

[Ive03] Ives F. E.: Parallax stereogram and process of making same, 04 1903. 1, 2

[IYS93] Isono H., Yasuda M., Sasazawa H.: Autostereoscopic 3-d display using lcd-generated parallax barrier. *Electronics and Communications in Japan (Part II: Electronics) 76*, 7 (1993), 77–84. `doi:10.1002/ecjb.4420760709`. 2

[JMY*07] Jones A., McDowall I., Yamada H., Bolas M., Debevec P.: Rendering for an interactive 360° light field display. *ACM Trans. Graph. 26*, 3 (2007). `doi:10.1145/1276377.1276427`. 2

[JUN*15] Jones A., Unger J., Nagano K., Busch J., Yu X., Peng H.-Y., Alexander O., Bolas M., Debevec P.: An automultiscopic projector array for interactive digital humans. In *Proc. SIGGRAPH '15* (New York, NY, USA, 2015), ACM, pp. 6:1–6:1. `doi:10.1145/2782782.2792494`. 1, 2

[Kak07] Kakeya H.: Moevision: simple multiview display with clear floating image. vol. 6490, pp. 6490 – 6490 – 8. `doi:10.1117/12.702713`. 2

[KKN16] Kajita H., Koizumi N., Naemura T.: Skyanchor: Optical design for anchoring mid-air images onto physical objects. In *Proc. UIST '16* (New York, NY, USA, 2016), ACM, pp. 415–423. `doi:10.1145/2984511.2984589`. 2

[LHKR10] Lanman D., Hirsch M., Kim Y., Raskar R.: Content-adaptive parallax barriers: Optimizing dual-layer 3d displays using low-rank light field factorization. *ACM Trans. Graph. 29*, 6 (2010), 163:1–163:10. `doi:10.1145/1882261.1866164`. 2

[LIK*05] Liao H., Iwahara M., Koike T., Hata N., Sakuma I., Dohi T.: Scalable high-resolution integral videography autostereoscopic display with a seamless multiprojection system. *Appl. Opt. 44*, 3 (2005), 305–315. `doi:10.1364/AO.44.000305`. 1, 2

[LLS17] Luo X., Lawrence J., Seitz S. M.: Pepper's cone: An inexpensive do-it-yourself 3d display. In *Proc. UIST '17* (New York, NY, USA, 2017), ACM, pp. 623–633. `doi:10.1145/3126594.3126602`. 2

[LNL*06] Lee H. J., Nam H., Lee J. D., Jang H. W., Song M. S., Kim B. S., Gu J. S., Park C. Y., Choi K. H.: 8.2: A high resolution autostereoscopic display employing a time division parallax barrier. *SID Symposium Digest of Technical Papers 37*, 1 (2006), 81–84. `doi:10.1889/1.2433641`. 2

[LWH*11] Lanman D., Wetzstein G., Hirsch M., Heidrich W., Raskar R.: Polarization fields: Dynamic light field display using multi-layer lcds. *ACM Trans. Graph. 30*, 6 (2011), 186:1–186:10. `doi:10.1145/2070781.2024220`. 2

[LWZ*13] Li W., Wang H., Zhou M., Wang S., Jiao S., Mei X., Hong T., Lee H., Kim J.: Principal observation ray calibration for tiled-lens-array integral imaging display. In *Proc. CVPR '13* (2013), pp. 1019–1026. `doi:10.1109/CVPR.2013.136`. 1, 2

[MHF*14] Monnai Y., Hasegawa K., Fujiwara M., Yoshino K., Inoue S., Shinoda H.: Haptomime: Mid-air haptic interaction with a floating virtual screen. In *Proc. UIST '14* (New York, NY, USA, 2014), ACM, pp. 663–667. `doi:10.1145/2642918.2647407`. 2

[MHKL05] Min S.-W., Hahn M., Kim J., Lee B.: Three-dimensional electro-floating display system using an integral imaging method. *Opt. Express 13*, 12 (2005), 4358–4369. `doi:10.1364/OPEX.13.004358`. 2

[MP04] Matusik W., Pfister H.: 3d tv: A scalable system for real-time acquisition, transmission, and autostereoscopic display of dynamic scenes. *ACM Trans. Graph. 23*, 3 (2004), 814–824. `doi:10.1145/1015706.1015805`. 1, 2

[MTLC92] Moore J. R., Travis A. R. L., Lang S. R., Castle O. M.: The implementation of a multi-view autostereoscopic display. In *IEE Colloquium on Stereoscopic Television* (1992), pp. 4/1–416. 2

[NZY*12] Nii H., Zhu K., Yoshikawa H., Htat N. L., Aigner R., Nakatsu R.: Fuwa-vision: An auto-stereoscopic floating-image display. In *Proc. SIGGRAPH Asia '12 Emerging Technologies* (New York, NY, USA, 2012), ACM, pp. 13:1–13:4. `doi:10.1145/2407707.2407720`. 2

[PPK00] Perlin K., Paxia S., Kollin J. S.: An autostereoscopic display. In *Proc. SIGGRAPH '00* (New York, NY, USA, 2000), ACM Press/Addison-Wesley Publishing Co., pp. 319–326. `doi:10.1145/344779.344933`. 2

[SMG*05] Sandin D. J., Margolis T., Ge J., Girado J., Peterka T., DeFanti T. A.: The varriertm autostereoscopic virtual reality display. *ACM Trans. Graph. 24*, 3 (2005), 894–903. `doi:10.1145/1073204.1073279`. 1, 2

[SSR11] Smoot L., Smithwick Q., Reetz D.: A volumetric display based on a rim-driven varifocal beamsplitter and led backlit lcd. In *Proc. SIGGRAPH '11 Emerging Technologies* (New York, NY, USA, 2011), ACM, pp. 22:1–22:1. `doi:10.1145/2048259.2048281`. 2

[TTH14] Takaki Y., Tokoro M., Hirabayashi K.: Tiled large-screen three-dimensional display consisting of frameless multi-view display modules. *Opt. Express 22*, 6 (2014), 6210–6221. `doi:10.1364/OE.22.006210`. 1, 2

[UIS*14] Ueda Y., Iwazaki K., Shibasaki M., Mizushina Y., Furukawa M., Nii H., Minamizawa K., Tachi S.: Haptomirage: Mid-air autostereoscopic display for seamless interaction with mixed reality environments. In *Proc. SIGGRAPH '14 Emerging Technologies* (New York, NY, USA, 2014), ACM, pp. 30:1–30:1. `doi:10.1145/2614217.2614275`. 2

[WLHR11] Wetzstein G., Lanman D., Heidrich W., Raskar R.: Layered 3d: Tomographic image synthesis for attenuation-based light field and high dynamic range displays. *ACM Trans. Graph. 30*, 4 (2011), 95:1–95:12. `doi:10.1145/2010324.1964990`. 2

[WLHR12] Wetzstein G., Lanman D., Hirsch M., Raskar R.: Tensor displays: Compressive light field synthesis using multilayer displays with directional backlighting. *ACM Trans. Graph. 31*, 4 (2012), 80:1–80:11. `doi:10.1145/2185520.2185576`. 2

[Yos11] Yoshida S.: fvision: Glasses-free tabletop 3-d display – its design concept and prototype –. In *Digital Holography and Three-Dimensional Imaging* (2011), Optical Society of America, p. DTuA1. `doi:10.1364/DH.2011.DTuA1`. 2

[YSK*11] Yoshida T., Shimizu K., Kurogi T., Kamuro S., Minamizawa K., Nii H., Tachi S.: Repro3d: full-parallax 3d display with haptic feedback using retro-reflective projection technology. In *2011 IEEE International Symposium on VR Innovation* (2011), pp. 49–54. `doi:10.1109/ISVRI.2011.5759601`. 2