Multi-user display systems, Compendium of the State of the Art.

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Abstract

One of the main shortcomings of most Virtual Reality display systems, be it head-mounted displays or projection based systems like CAVEs, is that they can only provide the correct perspective to a single user. This is a significant limitation that reduces the applicability of Virtual Reality approaches for most kinds of group collaborative work, which is becoming more and more important in many disciplines. Different approaches have been tried to present multiple images to different users at the same time, like optical barriers, optical filtering, optical routing, time multiplex, volumetric displays and lightfield displays among others. This paper describes, discusses and compares different approaches that have been developed and develop an evaluation approach to identify the most promising one for different usage scenarios.

Introduction

In many applications a group of users needs to collaboratively understand a spatial arrangement or relationships, e.g. can we fit this part into the machine, does this building fit into the planned plot, does this part of the molecule fit into the protein that it needs to control etc. Many of these problems require accurate spatial perception for each user and also require accurate spatial interaction, i.e.pointing at a specific element in the 3D world. In a normal projected display like a CAVE users can see and collaborate with each other, but only the tracked user gets the correct perspective when interacting with the 3D world, everybody else in the CAVE sees a distorted image. As long as they are looking in more or less the same direction as the tracked user the distortion is not too bad, but for example looking in the opposite direction (which happens easily when looking at an object that is inside the CAVE), will lead to inverted stereo and complete destruction of immersion.

Studies like the ones proposed by Pollock et al [1] back up this idea by demonstrating that even when perspective correct 3D is not needed for each user, collaboration times get significantly longer when participants stay at different positions compared to the same location relative to the center of perception (CoP).

The design challenge lays in creating a system that can display different images in a common area occluding all but the correct image for each user. This challenge is not something fundamentally new; different approaches have been attempted to multiplex images from a single display to different users providing a correct perspective for each one; in this paper we are going to describe and discuss different projects that have been developed multi user VR experiences and the different challenges each project has faced.

In [2], Mark Bolas presents a promising classification on the different approaches for doing multiuser immersive display systems. He proposes in his research that all these attempts convey into a "Solution Framework" which is split into four general categories: Spatial Barriers, Optical Filtering, Optical Routing and Time Multiplexing.

In addition to these categories it is worth mentioning volumetric displays and light field displays, which are relevant to the multi user viewing topic even though they achieve multi user perspective through a totally different approach.

Spatial barriers

Spatial barriers take advantage of the display's physical configuration and user placement to display users' specific views. Essentially they form a mechanical barrier that lets each user see a subset of the underlying displays' pixels.

The spatial barriers approach has been around for a while. In the late 80's Sandin e.a. [3] proposed a variety of methods for producing "Phscolograms". Autostereograms that use barrier strips to separate images from each eye giving the users a sense of depth. These Phscolograms use static printed images that he later used to introduce "The Varrier" system [4, 5, 6]. Here, their system uses a tiled set of parallax barriers displays that provide autostereoscopic virtual reality for a single user.

Schwerdtner on a similar way in 1998 comes up with the Dresden display [7]. In this project, they propose a display that consists of a flat panel display, a parallax barrier and a tracking system; it works by moving a parallax barrier side to side and slightly forward/backward in response to the observer's position. The main challenge for their approach is the latency due to the mechanical nature of the adjustment. Their system also provided a correct perspective views for only one user.

Later on, Perlin e.a. [8] presents a hybrid system that uses both time multiplex and spatial barriers approach to produce an autostereoscopic display. They generate a parallax barrier that gets accommodated to the user's position; the barriers expand/contract and move accordingly to the user movement. They use a DLP micro-mirror projector and a Ferroelectric Liquid Crystal (FLC) shutter to start/stop each temporal phase.

Along the same lines as Perlin's work, Peterka e.a. propose a dynamic parallax system called Dynallax [9, 10]. This system varies the barrier period eliminating conflicts between users supporting up to two players with autostereoscopic views. Dynallax consists of a dual stacked LCD monitor where a dynamic barrier gets rendered in the front display and a rear display produces the imagery, a small cluster to control the displays and a head tracker to accommodate views for each user's position.

Mashitani proposes as an alternatve the "Step barrier" system [11]. This technology overcomes the problem of conventional parallax barriers of image degradation on the horizontal direction. Here, they distribute the resolution on both horizontal and vertical directions by creating a spatial barrier that contains tiny rectangles arranged in the shape of stairs instead of vertical stripes.They also expose three methods for generating imagery for these systems: A high quality slow process method called "thinning out", a "waste less" method which is less processor intensive and a hybrid approach which is a combination of both.

Zhang e.a. [13] proposes an autostereoscopic system based on time division quadplexing parallax barrier that can display full image resolution per view and holds continuous viewing zones. They do this by stacking two LCD panels; one screen for rendering images and the other for generating barriers. With time division quadplexing applied they achieve full resolution. They display right-eye image of a stereo pair to the two viewpoints on the right side and do the same to the left-eye images obtaining four viewpoints.

Another interesting approach for working with spatial barriers is the PIT (Protein Interactive Theater) project [15]. Here, Arthur e.a. use a dual screen stereo display system placed orthogonally for two users. Each user is tracked and the virtual content is augmented in real space. The two users interact and point at positions of the model within the same real world as the projections match for each user.The system only works for two users and there is always the possibility of one person to "peek" at the other's person view and perceive a distorted image (figure 1).

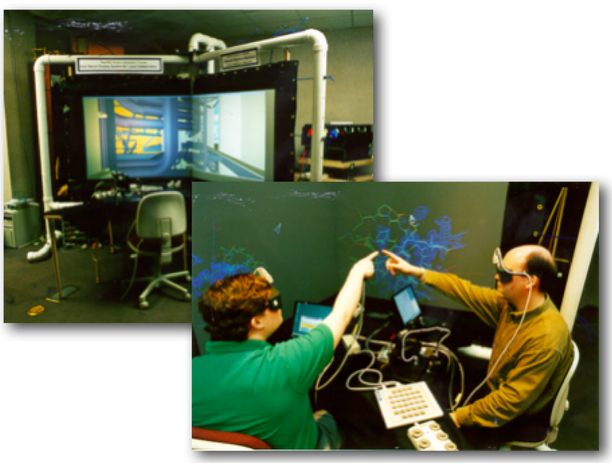

Figure 1. *The PIT: Protein Interactive Theater [15].*

Along the same lines, Schreer e.a. [16] present a general concept for a two local multi-user video conference system. They describe the design and arrangement of the system and a general multi-view video analysis. In their design they propose a multi-view display with 2 "view cones" with significantly different perspectives for each participant. There is no head tracking and only two users are able to use the system.

A larger-scale alternative is the AVIE project by McGinity e.a. [17] They introduce a VR theatre that uses a 360 degree screen with omnistereo projection, surround sound and marker less tracking. They use 12 projectors in a cluster of 6 dual xenon PCs.

Another approach other researchers follow is the assignment of subsections of screens and personalize these sections for each user; for example. In the Pen and Paper paradigm research [18]. Ehnes e.a. uses a virtual table in a workbench like setting and presents a multi viewer system by tracking participants and presenting unique perspective correct images on subsections of the table for each user. Their project works both on 2D and 3D with shutter glasses.

Marbach [22] presents the idea of rendering different users' point of views in separate parts of the screen based on their position and head orientation; these views are blended together in a blend area between them. When users look at nearby points, their viewpoints are averaged and one image is rendered for those users. Later [23], he uses geometry shaders to improve the rendering rate and does an extensive user study comparing multi-viewer approaches [24] (figure 2).

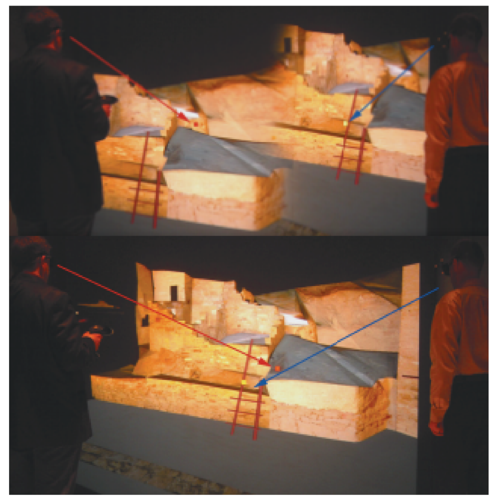

Figure 2. *Image blending and view clustering for multi-viewer immersive projection environments [22].*

Schulze [25] presents a similar idea like Marbach's, but their approach aims at rendering the point on the screen a user looks at from that user's eye point whenever possible, while allowing some distortion in a user's peripheral view if other user's renders are nearby. They mention their approach works best on scenarios with data sets but not in architectural models or similar environments.

Following the idea of using parts of the screen for multiplexing views, Kitamura e.a. proposes the Illusion hole [19]. In this research, their system allows 3 or more people to simultaneously observe individual stereoscopic images from their own viewpoints by tracking each users' heads. The system consists of a normal display and a display mask that has a hole in its center; the display mask is placed over the surface at a certain distance and each user sees their area with shutter glasses. Later [20] they present a small-scale simplified IllusionHole prototype that uses 2 liquid crystal projectors and circular polarizing filters with passive stereoscopy (figure 3).

A related but very different approach is presented by Nashel e.a.: the Random Hole Display [21]. Their prototype consists of a plastic barrier separated from a 20" display by a glass spacer. The barrier pattern is cut with a Poisson disk distribution of holes, the display has physically discrete subpixels and each color channel is calibrated separately. By randomizing the barrier pattern, their system eliminates the repeating zones found in regular barrier and lenticular autostereoscopic displays. Their system supports up to 4 different views without stereoscopy or 2 with stereoscopy.

Finally, Lanman e.a. in [26] introduce a technique that op-

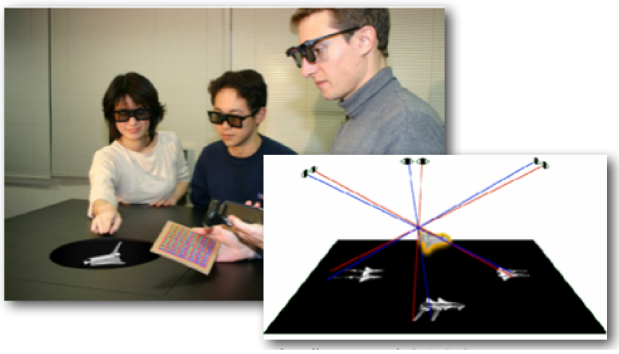

Figure 3. *The Illusion Hole [20].*

timizes automultiscopic displays. Here, they propose content-adaptative parallax barriers where the display elements are optimized for multi-view content. They create a prototype with a dual-stacked 120hz LCDs separated by 1.5cm. The rear layer of their prototype is unmodified while the front layer acts as a spatial light modulator, they removed the front and rear polarizing films and replaced the front polarizer diffusers with a transparent polarizer.

Optical routing

Optical routing uses the angle-sensitive optical characteristics of certain materials to direct or occlude images based on the user's position [2].

In 1994, Little e.a. presented a design for an autostereoscopic, multiperspective raster-filled display [27]. Here, they propose a hybrid time multiplex/optical routing approach. They use an array of video cameras to capture multiple perspective views of the scene and feed these to an array of LCTVs. The viewing screen is formed by either a holographic optical element or a Fresnel lens and a pair of crossed lenticular arrays. Resolution is limited by the LCTV projectors and they use a lot of projectors / cameras to provide multiple views.

Van Berkel e.a. in [28, 29] presented a prototype display using a LCD and a lenticular lens from Philips Optics to display 3D images; they slanted the lenticular lens with respect to the LCD panel in order to reduce the "picket fence" effect.

Later in the same year, Matsumoto e.a. [30] propose a system that consists of a combination of cylindrical lenses with different focal lengths, a diffuser screen and several projectors to create a 3D image.

Omura presents a system that uses double lenticular lenses with moving projectors that move according to the tracked user's position to extend the viewable area [31]. Their system needs a pair of projectors per person and their projectors move to adjust each user's position. Their system suffers from latency due to the mechanical movement.

Eichenlaub instead proposes a hybrid time multiplex/optical routing 21" autostereoscopic display [32]. Their display produces eight views at 60hz.The authors report loss of brightness and contrast caused by the beam splitter along with a washed out blue color produced (figure 4).

In 2001 Son e.a. proposed a hybrid optical routing/spatial barriers approach with an autostereoscopic display with 16 views [33]. Here, they use two 6.5inch LCD projection panels for stereo

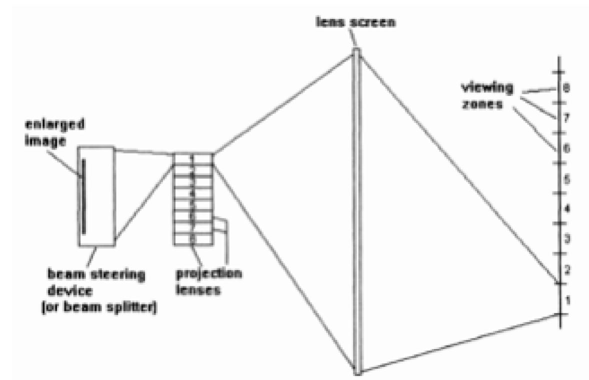

Figure 4. *Eichenlaub - Multiperspective look-around autostereoscopic projection display using an ICFLCD [32].*

image display, two lamp modules for backlighting, a screen projection for magnifying the stereo image and a liquid crystal diaphragm for viewing zone forming with a head tracking system to track users.

Alternatively Jeon e.a. propose a design for a multi-view 3D display system based on focused light arrays (FLA) using a reflective vibrating scanner array (ViSA) [34, 35]. They present two possible implementations that use a parallel laser beam. The first one uses a vibrating curvature-compensated mirror scanner array while the second uses a vibrating diamond ruled reflective grating scanner array.

Later in 2002, Lipton proposes the Synthagram [36], a system that consists of an LCD Screen with a lenticular screen that overlays the LCD display. They angle a lenticular screen in order to reduce moire patterns and their system uses nine progressive perspective views from a single image.

Matusik proposes a system that consists of an array of cameras, a cluster of networked PCs and a multi-projector 3D display with the purpose of transmitting autostereoscopic realistic 3D TV [37]. They record imagery with a small cluster of cameras connected to PCs that broadcast the recorded video which is later decoded by another cluster of consumer PCs and projectors. Their 3D Display consists of 16 NEC LT-170 projectors that are used for front or rear projection. The rear projection approach consists of two lenticular sheets mounted back to back with an optical diffuser material in the center and the front projection system uses one lenticular sheet with a retro reflective screen material.

Another optical routing approach use is the display proposed by Nguyen e.a. [38, 39]. Here, they present a special display that consists of a screen with three layers that have directional reflections for projectors so that each participant sees a customized image from their perspective. Their system supports up to five viewing zones and requires a projector per participant(figure 5).

Takaki e.a. proposes a system that can produce 72 views [40]. Their project consists of a light source array, a micro lens and a vertical diffuser (a lenticular sheet). They mention that as the horizontal positions of all light sources are different, rays from different light sources proceed to different horizontal directions after passing through the micro lenses thus generating different views. Finally they conclude that it's difficult to fabricate a large micro lens array and that unused pixels remain at the corners of the LCD panel.

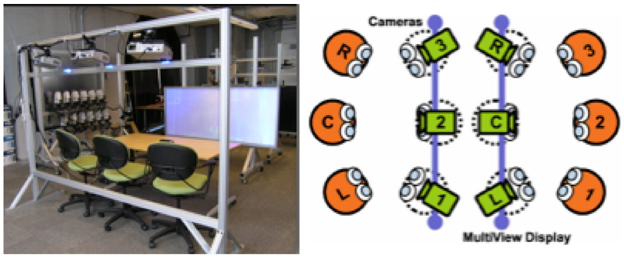

Figure 5. *Nguyen - Multiview: improving trust in group video conferencing through spatial faithfulness [39].*

Takaki also discusses a multiple projection system that is modified to work as a super multiview display [41, 42, 43]. Here, they attach a lens to the display screen of a HDD projector and by combining the screen lens and the common lens, they project through an aperture array. This aperture array is placed on the focal plane of the common lens, and the display screen (a vertical diffuser) is placed on the other focal plane. Hence, the image of the aperture array is produced on the focal plane of the screen lens. With this, the image of the aperture array gets enlarged generating enlarged images that become viewpoints. The authors comment that there is some discontinuity between the different generated views when the observation distance is different from the distance to the viewpoints.

In 2009 Takaki and his team introduced a prototype panel that can produce 16 views [44]. They built a LCD with slanted subpixels and a lenticular screen. They placed a diffusion material between the lenticular sheet and the LCD screen in order to defocus the moire pattern but increased the crosstalk among viewpoints. They mention that by slanting the subpixel arrangement instead of the lenticular sheet, they can increase the number of views and reduce the crosstalk significantly but the optical transmittance of the display decreases.

Finally, in 2010 Takaki e.a. combine several 16-view flat-panels with slanted subpixels [44] and create a system with 256 views [45]. They superimpose different projected outputs of the panels on a single vertical diffuser; then, the multiple viewing zones for each panel are generated on an incident pupil plane of its corresponding projection lens. Each projection lens projects to the display surface of its corresponding flat panel system on the common screen and finally a screen lens is located on the common screen so the lens generates viewing zones for observers.

Another system that takes advantage of the optical routing approach is the Free2C display, a project proposed by Surman [46]. Here, they created a single viewer autostereoscopic display using a head tracker. The display accommodates the head movement of the viewer by continually re-adjusting the position of the lenticular lens in relation to the LCD to steer the stereoscopic views onto the eyes of the viewer.

Similarly, Brar e.a. use image recognition to track users' heads to produce multiple steerable exit pupils for left and right eyes [47, 48]. Here, they describe the design and construction of an autostereoscopic display that produces a stereo pair on a single LCD by simultaneously displaying left and right images on alternate rows of pixels. They propose steering optics controlled by the output the aforementioned head tracker to direct regions, referred as exit pupils to the appropriate viewers' eyes. Their prototype is not optimal due to insufficient brightness and instability in the holographic projector and mention doesn't support multiple views besides the produced for each eye.

Kooima e.a. [49] uses 24" and 42" 3DHD Alioscopy displays. They propose a system that consists of scalable tiled displays for large field of views and use a generalization of a GPU based autostereoscopic algorithm for rendering for lenticular barriers. They tried different methods for rendering different views but had issues where they perceived repeated discontinuities, exaggerated perspectives and as the displays pixels cannot be moved smoothly but in discrete steps; when the tracked viewer moved into transition between channels, the user began to see the adjacent view before the channel perspective was updated to follow the user's head. They mention that depth and orthostereo remain the most significant lacking issues of their system.

Later on, Sonoda e.a. propose a display that uses multi-varifocal lenses aligned with a high-speed display [50]. They layer many 2D images by changing their depth position using a multi-varifocal lens. They have a projector array that uses LED sources where images are projected to the same position of a screen and by time multiplexing these projectors quickly, depth-sampled 2D images on the screen are displayed at high speed.

Later in 2012, Kim e.a. came up with an interesting way of using optical routing by exploiting a physical property of Twisted Nematic LCDs [51]. Here, they present a pure software solution that benefits from Twisted Nematic LCD screen attributes in order to provide different views depending on the view angles on these types of screens. They created an algorithm that analyzes the color curves for each color and depending on the viewing angle they modify pixel colors to match the contrast from said angle. They provide images for different users by doing either spatial multiplexing by interlacing images in the spatial domain with alternating pixels or time multiplexing by alternating said images, and with visual persistence they create the perception of a single continuous image. They comment that loss of saturation, brightness and contrast is perceived.

In a more traditional way using newly available hardware, Surman [52] describes a head tracker displays that provides autostereoscopic imagery. The system uses pico projectors that project left and right images to a retro reflecting screen and moves projectors to compensate for the user's position. They mention they get specular reflections from the screen producing vertical bright lines.

In 2014 Zang e.a. propose a frontal multi-projection autostereoscopic display [53]. Their approach consists of an 8 staggered projectors and a 3D image guided screen. The 3D image screen is mainly composed of a single lenticular sheet, a retro-reflective diffusion screen and a transparent layer that is filled between them to control the pitch of the rearranged pixel stripe in interlaced images. Their system is space efficient compared to previous approaches that produce light from the back of the screen. They mention that they perceive loss of intensity and increased crosstalk outside of the system boundaries

Hirabashi e.a. propose a system composed of frameless multi-view displays in [54]. Each module consists of a multi-view flat-panel display, an aperture, an imaging lens, a screen lens and a vertical diffuser.

Jones [55] proposes a system that contains 216 closely spaced video projectors projecting to a screen material. This material consists of an anisotropic light shaping diffuser and generates autostereoscopic images for a large number of viewers (figure 6).

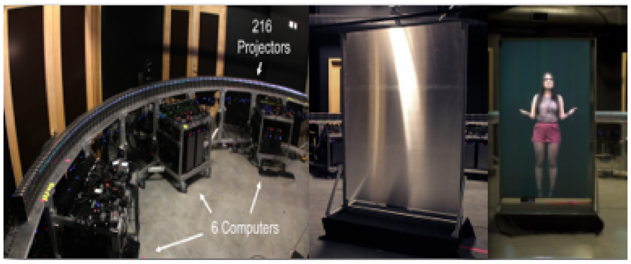

Figure 6. *Jones - An automultiscopic projector array for interactive digital humans [55].*

Finally, a commercially available display one can get hands on is the Looking Glass [56]. This display uses lenticular lenses for generating 45 unique viewpoints to the viewer, a high refractive index material for shifting the focal plane and an optical film for further sharpening the generated images.

Optical filtering

This technique involves systems that filter viewpoints using light's electromagnetic properties, such as polarization and wavelength [2].

De la Re e.a. propose an approach based on Agrawala's work [79] but with a fraction of the cost [57]. Here, they combine active shutter glasses, use anaglyphic filters and produce two mono channels from the stereo channel to provide audio to each user (figure 7.

Figure 7. *Inexpensive 3D Stereo for Two Users Using a Single Display [57].*

In 1999, Benton e.a. propose a system that lets multiple viewers (3) visualize different images at the same time [58]. Here, they use interdigitated strips of polarized sheets (of orthogonal polarization selection) located on Twisted-Nematic LCD panels, a large lens and a video processing software for recognizing faces. The system becomes noticeably slower when three persons are using it.

Schmidt e.a. introduces Wavelength-selective filter arrays [59]. These filter arrays are mounted in front of a flat panel (TFT/Plasma) and produce eight perspective views so multiple observers can get images at the same time. Wavelength selective filter arrays consist of many small wavelength filters which are combined in a regular pattern. This pattern matches the subpixel structure of the panel they get attached to and because of the different wavelength filters the light from the subpixels is directed into different directions. These filters suffer from brightness reduction and transitional areas that are perceived in the projected image.

Another interesting approach to optical filtering multiplexing is Kakehi e.a.s work [60, 61, 62]. They introduce the Lumisight table which is a horizontal tabletop display that uses a special screen called lumisty and a fresnel lens. Their system combines the lumisty films (which become opaque depending on the view direction) and use a lens with four projectors to display different images, one for each user's view.

Jorke and Simon propose a wavelength multiplex approach that takes into account the nature of the human eye [63, 66]. This approach is using interference filters and is thus called INFITEC (figure 8). Visualization by wavelength multiplexing encodes image information in different spectral ranges by using a narrower wavelength band in order to increase the number of images that can be shown in parallel. In their research, they code the image information of one image into three narrow bands in parallel (red, green, blue). Each eye uses a narrow bandwidth filter that has a triple band characteristic to transmit selectively the narrow bands associated with the image content encoded [64, 65].

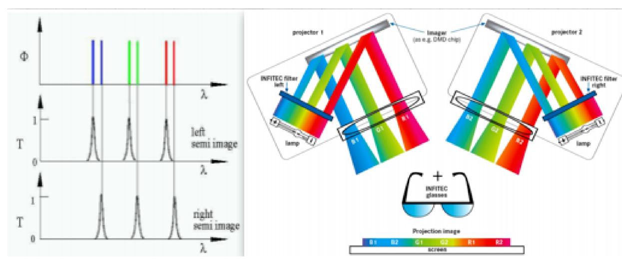

Figure 8. *Stereo projection using interference filters [63].*

Another approach that uses optical filtering is Scritter [67]. Here, Hamada e.a. proposed a system that enables the superimposition of invisible messages on a large screen while sharing a movie. They achieve this by using 2 projectors attached to different circularly polarization plates, a silver screen and glasses that have the same polarizing lenses. Their system doesn't scale up more than for two different images.

Along the same lines, Nagano e.a. enables superimposition of multiplexed images using special configured polarized glasses [68]. Here, they use a hybrid time multiplex and optical filtering approach based on [90]. They use two DMD projectors to project different images and employ the same type of filters in the shuttered glasses being able to display different content with the filters. Their system only supports two users.

Subsequently, Nagano e.a. present *ScritterHDR* [69]. Here, they introduce a system based on *Scritter* [67] that enables the display of multiplexed hidden images using a hybrid approach that relies on time multiplex and optical filtering. They hide images based on the project proposed in [68].

Kim on the other hand, proposed a system capable of displaying full colored stereoscopic imagery with anaglyph filters in [70]. Here, they follow a hybrid approach of time multiplexing and optical filtering; their system allows full-color 3D imagery by switching the color property on the user glasses.

In 2011, Simon e.a. enhanced their research done in [63] and demonstrate an improvement in color transmission performance for Ultra High Performance (UHP) projectors by minimizing the difference between color and luminance between left and right eyes' filters [71].

Another use of optical filtering can be found in Kakeya e.a.'s work [72]. Here, they propose a time-division multiplexing anaglyph method that reduces flickering at lower refresh rates (60hz). They do this by separating the color components of the image in Green and Magenta (red and blue) and showing these components alternatively.

Later on, Zhang e.a. proposes [73] which is based on Kakeya's e.a. work [72]. They propose an autostereoscopic display that uses an active anaglyph parallax barrier system that uses time multiplexing for supporting different views. They created a prototype that consists of two screens; one screen for the parallax barrier and the other screen for displaying the imagery. Their system supports up to four users.

Gaudreau e.a. describes a concept for an autostereoscopic system that combines regular 3D LCD at 120Hz with a vertical patterned active shutter panel and a head tracking system [74]. Here, they mention that the parallel barrier can be made of patterned QW retarder film and a circular polarizer.

Littfass e.a propose a multiplex hiding imaging technology which works with polarization filters enabling multiple users to watch different contents on the same display [75].

In the ExPixel project [76], Suzuki e.a. use a 3D flat panel based on a line-by-line polarized device to multiplex-image hiding with passive polarized glasses, their work is based on *Scritter-HDR* and 2x3D and their technology is similar to SONY's SimulView technique [77].

Finally, Suzuki e.a. introduces the *FamiLinkTV* system [78]. Here, they demonstrate the 4th iteration of the *Scritter* [75] system developed for usage in the family room; it works the same as *Scritter* and is able to display content on the naked eye or hidden / extra content using polarized glasses. The system only works for two users.

Time multiplex

Time multiplexing encompasses the solutions that use time-sequenced light and shutters to determine which user sees an image at a given point in time [2].

The majority of the citations that use this technique relate mostly to Agrawala's work with the two user responsive workbench [79]. In his research, Agrawala e.a. presents a virtual reality system that allows two users at the same time to view individual stereoscopic image pairs from their own viewpoints. The system tracks head positions of both users and computes images for each eye. They compute 4 images, one for each eye. These images are presented in sequence and they separate users by modifying a single user shutter glasses and adding a third state where both eyes are closed so they can display the other user's images (figure 9).They report that image flicker and crosstalk is perceived.

Dodgson e.a. [80, 81] describe the Cambridge display. It consists of a high speed LCD, a fresnel lens and a series of abutting bar shaped light sources that with time multiplexing can show

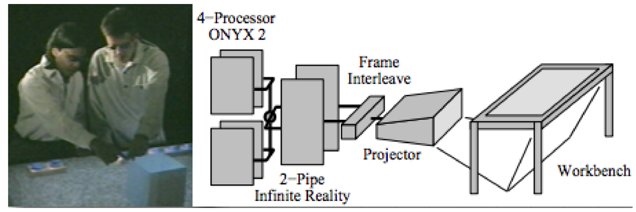

Figure 9. *Agrawala - Two user responsive Workbench [79].*

different images for each eye giving a sense of depth. Later on in [82], the team proposes a 28 view, 25" display that combines time sequential and multiprojector technology. Following their research, the team presents a follow up on the work done in [82] proposing a 50" Time-multiplexed autostereoscopic display [83]. Here, they design a time multiplexed-display for two users; the system contains two subsystems each with 3 CRTs, one for each color (red, green, blue), for each person and runs at 30Hz. They produce 15 views at 640x480.

Similarly, Shoemaker e.a. [84, 85] propose a system that works with a modified version of a Stereographics system [86] that uses time multiplex approach and hides private information from the other users. The system supports two users.

In 2002, Blom e.a. present a general idea of a multi-user projection-based system that works with two users with stereoscopy and four users on monoscopic views [87]. They use shutter glasses to separate views and enable four buffers for video multiplexing by combining two stereoscopic streams.

Later on, in [88], Froehlich presents a system that shutters four projectors to support two users with correct perspective views using time multiplexing with a micro controller. They scaled their system up to four users at 320Hz, two projectors per user with highly customized shutter synchronization and high refresh rates for enabling time multiplexing (figure 10).

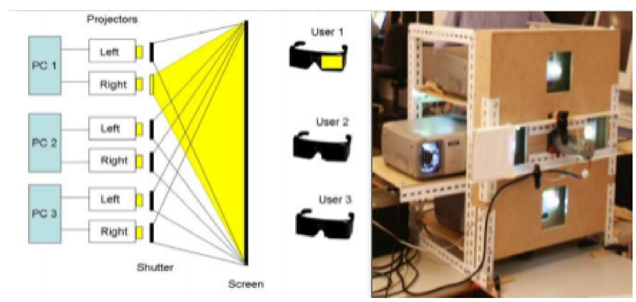

Figure 10. *Froehlich - Implementing multi-viewer stereo displays [92].*

Cossairt e.a. talk about a collaboration between Cambridge and MIT for a view sequential display based on DMD technology in [89]. They use ferroelectric LCD shutter glasses for stereoscopy and interleave frames on a time multiplexing basis.

McDowall e.a. use a time multiplex approach to hide images with a shutter [90]. Here, they display imagery at 1.8khz using DMD devices, in a 60th of a second they display the image everyone can see 20 times and the hidden image gets displayed twice along with a negative of the same image again twice. They are able to see the images through a shutter.

In 2005, Blach e.a. presents a design of a multi-view stereo system based on shuttered LCD-projectors and polarization [91], where polarization is used to separate eyes and shutters to separate users. They built a custom micro-controller for controlling the shutters and each user uses one projector pair.

In the same year, Froehlich proposes a hybrid multi-user stereo system based on shuttered LCD projectors and polarization [92]. The combination of these techniques allow them to present images for more than one stereoscopic view on a single projection screen. Their system uses two projectors per person and eye separation is done through polarization while shutters are used for separating users. They mention that the polarization and shuttering provides twice the brightness versus a shutter only approach.

Later on, Kupiec e.a. [93], propose a time multiplexed display that can produce eight views jitter and flicker free. They achieve this by using a high speed mirror device (DMD) that is driven by a custom FPGA driver and a custom GPU program.

Pranav in the ThirdEye system [94] modified LCD Shutter glasses and synced them with a screen doing frame interleaving for displaying unique images for each user.

Similarly the HELIUM3D project (2008-2011) [95, 96, 97] is an autostereoscopic display system that provides time multiplexed views by forming regions referred to as exit pupils where a particular image can be seen over the complete area of the screen so a stereo image pair can be directed to each viewer.

Later, in 2011, Kulik [98] introduces C1x6. A projection-based stereoscopic hybrid display system for six users. They use six customized DLP projectors and each one projects a time sequential image in one of the primary colors and by differently polarizing the light output from the first set of three single color projectors (RGB) than the second set, they are able to project 12 separable full-color images onto a projection screen.

Another approach proposed by Beck e.a. that uses time multiplexing is an immersive telepresence system that allows distant groups of users to collaborate in a shared task space [99]. Here, they use two projection-based multi-user 3D displays and Kinects to do reconstruction of the other users in the virtual world. If a remote user is touching the same point on a virtual model, their fingers meet in the space. Their system can accommodate up to six users respectively.Their approach relies on virtual users to be able to increase the number of users in the system.

Lissermann proposes a set of interaction and visualization techniques for multi-view table tops [100]. Here, they use a 52” Philips 3D display at 120Hz along with active shutter glasses tracked with two Kinect cameras for user tracking and hand recognition. The shutter glasses switch between transparency levels at high frequency and they map each shutter glass to a unique individual output letting users have a personalized view; their challenge is that the refresh rate defines how many separate views can be offered.

Another non-conventional hybrid time-multiplex Optical Routing approach is the use of directional backlighting for selectively light certain portions of the screen and displaying different images through time multiplexing. Hayashi e.a. [101] use directional backlighting for producing a 23” full resolution autostereoscopic panel while Liou e.a. [102] use the same principle with a 240Hz display and a custom FPGA to show content for four different views.

Geng, on the other hand, describes an optical design technique for a multiview 3D display that uses only one projector [103]. They generate multiple views with a hybrid approach of time-multiplex and optical routing techniques. Their prototype consists of a single high-speed projector with specialized optical components, a scanning mirror and a reflective mirror array. Images are generated sequentially and projected via the specially designed optical system from different viewing directions towards the screen.

In 2016 Koutaki e.a. present a research on how to do a multiview display using a DLP projector and modified active shutter glasses that display grayscale images for shuttering instead on - off states [104]. They use a time division method like Froelich [88] and Agrawala [79] and use image decomposition for displaying the images. Their proposed model prevents projection of extreme black patterns reducing flickering of the display.

Finally a peculiar approach on the time multiplex approximation can be found in Barnum’s e.a. work in [105]. Here, they present a system with a single projector and layered displays using lines of water drops and illuminating each row of lines separately while they fall, creating a sense of multiple displays. Their biggest challenge lays in its resolution, complexity of the system and refresh rate.

Volumetric displays

In volumetric displays, the image is produced within a volume of space where this volume can be either virtual or real [47] and the content is always confined within the physical device enclosure [106].

In 2001. Favalora e.a. [107] talk about an 8 color multiplanar volumetric display, they describe the architecture both in hardware and software and talk about the different components. Their system provides volume-filling imagery of 90 million voxels by using a XGA-resolution projector that illuminates a rotating screen with rapid sequence of 2D ”image slices” (figure 11).

Figure 11. *Favalora - Volumetric three-dimensional display system with rasterization hardware [107].*

Sullivan proposes the DepthCube [106]. Here, he exposes a solid-state multi-planar volumetric display where a DLP projector projects slices of a 3D scene into a stack of liquid crystal scattering shutters.

Otsuka e.a. on the other hand, propose the Transpost system [108]. They describe a system that works with a directional-reflection screen, mirrors and a standard projector. Their system works by projecting content into a spinning directional-reflection screen with a limited viewing angle.

As a similar approach, Jones e.a. propose a set of rendering techniques and a system that consists of a high speed video projector, a spinning mirror covered by a holographic diffuser and a FPGA custom circuitry to decode specially crafted DVI signals [109].

Another unconventional volumetric display comes out of

Eitoku e.a.'s work [110]. Here, they propose a "controllable particle display". This system displays 3D objects by filling space with water drops falling from a tank; the objects then can be observed by projecting a set of tomographic images synchronized with the position of the water drops.

In 2006, Bimber e.a. describe a volumetric system [111]. This system consists of two main parts, a convex assembly of half silvered mirrors and a graphics display. They created 2 prototypes; the first one consisting of 4 half silvered mirrors assembled as a truncated pyramid providing views for up to 4 users (one on each side). The 2nd prototype consists of a truncated cone and they placed the mirror assemblies on top of a projection screen. The cone provides a seamless surround view onto the displayed artifact. To achieve stereoscopy they use active shutter glasses and head tracking is done with an electromagnetic tracker.

Nayar e.a. proposes an inexpensive low resolution volumetric display in [112]. Here, they precisely illuminate randomly lasered induced cracks on a material and render a volume.

In a more peculiar way, Kimura e.a. [113] use laser plasma technology to make flashpoints in the air. Their device uses a plasma emission phenomenon near the focal point of focused laser light to produce plasma bursts in the air (figure 12).

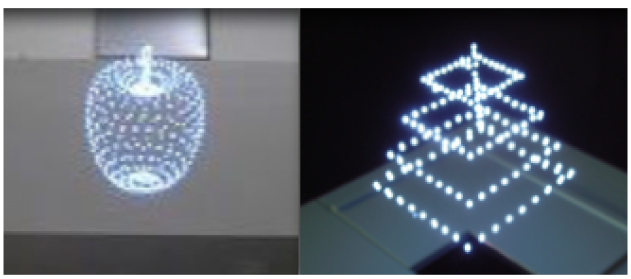

Figure 12. *Kimura - Laser produced 3D display in the air [113].*

Cossairt proposes an occlusion capable volumetric display [114]. Here, he describes and demonstrates a hybrid volumetric display that has 128 views. Their device is capable of reproducing viewer perspective effects such as occlusion; they achieve this with an horizontal projector that illuminates a rotating vertical diffuser with a series of multi-perspective renderings of a 3D scene.

Finally, Gocho e.a. [115] propose an extension of the depth fused 3d system proposed by Suyama in [116]. Here they use four images from a screen to fuse imagery in order to give a sense of depth, these four images are synthetized and located in a screen that gets redirected with mirrors and half mirrors. This helps them out getting rid of the bulkiness that a DFD display carries as they use several screens.

Lightfield displays

In light field displays, the light emitted from a point on screen varies with the direction. These displays are subdivided in two categories: 1. Light emitted from a point on the screen changes with angle so real 'voxels' are produced in front of screen and 2. Multi-beam displays that use a laterally moving aperture formed on a ferroelectric screen that controls light output from a fast projected image on a screen located behind it [95].

In 2011, Wetzstein e.a. describe a technique to do image synthesis on layered displays with light-attenuating materials [117]. Their prototype uses static images and tomographic techniques for rendering high resolution volumetric frames (figure 13). Their technique only works on static images due to the length it takes the solver to calculate optimized values (12min on average).

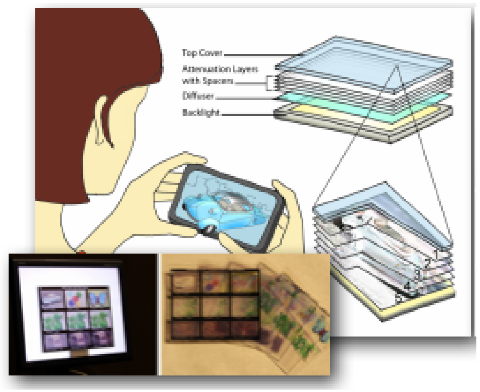

Figure 13. *Wetzstein - Layered 3D tomographic image synthesis [117].*

Lanman e.a. introduce polarization field displays [118]. Here, they stack a set of LCD panels with a single pair of crossed linear polarizers. They model each layer as a spatially controllable polarization rotator (opposed to conventional spatial light modulators) and produce color by using field sequential color illumination with monochromatic LCDs; with this approach their prototype produces increased brightness, higher resolution and extended depth of field (figure 14).

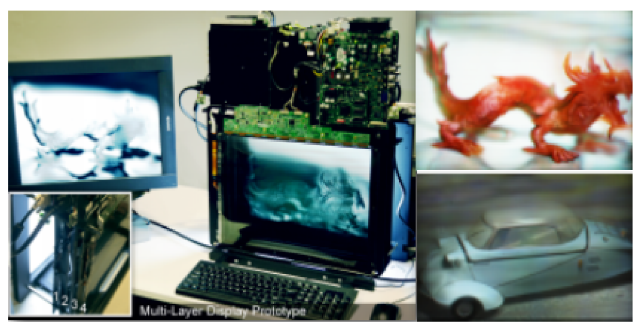

Figure 14. *Lanman - Polarization fields: dynamic light field display using multi-layer LCDs [118].*

Later on, in 2012. Wetzstein et al. take advantage of the principle of multilayer displays, high-speed displays and directional backlighting and introduces tensor displays [119]. These displays consist of a single backlight with layered displays with lenses in between. By intersecting each light ray between the layers they get a representation of a tensor and the points of intersection define the location in the tensor corresponding to each ray. They use nonnegative tensor factorization to get an average perceptual image that assembles the scene. An issue they face is that it only works for static images as it takes time to calculate the optimal pixel representations.

Finally, Chen uses a Kinect and vision based tracking system in combination with light field displays to significantly increase the depth of field and field of view of the displays from 10x10 to 100x40deg [120]. They mention that they achieve good image quality for only 2 views.

Conclusions

Hybrid approaches try to exploit the best from the different aforementioned techniques and are commonly use to either generate stereoscopy or increase the number of engaging users.

It is clear that parallax barrier methods generally face challenges regarding brightness (with some exceptions) and the projects exposed here cannot produce more than two views with stereoscopy. Even though there can be room for improvement, the method itself makes it hard to separate users due to physical limitations.

Most of the work on Optical Routing presented here is relatively old. Some of the challenges that the projects had can proably be solved with current technology like increased resolution on displays among others. It is clear that there is still some room for improvement on this area.

Optical filtering approaches are very limited by the nature of their filters for separating users (when using polarizing techniques) and also brightness is another factor that gets affected negatively. There is room for improvement in this area and techniques like the ones proposed by INFITEC back up this but designing an optical filter that is robust and direction-independent to be usable for glasses is not an easy task.

Time multiplexing is an interesting technique that with fast enough refresh rates can increase the number of views. Still, the added synchronization complexity, custom circuitry and shuttering nature of the approach generates new challenges that need to be solved like brightness and flickering among others

One of the biggest challenges volumetric displays face at present is resolution and occlusion. Unfortunately, with the nature of the approaches users cannot pinpoint certain parts directly of the generated models, as it is potentially ery dangerous to put their hands inside the display volume. This could be a problem on scenarios that users need to interact without virtual wands with the generated content

Light field displays is an active area of science with a lot of research being carried out right now. One of the biggest challenges this approach faces is the fact that there are no out of the box solutions and everything needs to be built from scratch, long processing times for generating frames and reduced viewing angles also offer a lot of room for research.

In conclusion it has to be said that there is no silver bullet, but that the classical methods of optical routing and parallax barriers still promise the best results with modern technologies.

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References

[1] Pollock, B., Burton, M., Kelly, J. W., Gilbert, S., & Winer, E. (2012). The right view from the wrong location: Depth perception in stereoscopic multi-user virtual environments. IEEE transactions on visualization and computer graphics, 18(4), 581-588.

[2] Bolas, M., McDowall, I., & Corr, D. (2004). New research and explorations into multiuser immersive display systems. IEEE computer graphics and applications, 24(1), 18-21.

[3] Sandin, D. J., Sandor, E., Cunnally, W. T., Resch, M., DeFanti, T. A., & Brown, M. D. (1989, September). Computer-generated barrier-strip autostereography. In OE/LASE'89 (pp. 65-75). International Society for Optics and Photonics.

[4] Sandin, D. J., Margolis, T., Dawe, G., Leigh, J., & DeFanti, T. A. (2001, June). Varrier autostereographic display. In Photonics West 2001-Electronic Imaging (pp. 204-211). International Society for Optics and Photonics.

[5] Sandin, D. J., Margolis, T., Ge, J., Girado, J., Peterka, T., & DeFanti, T. A. (2005, July). The Varrier TM autostereoscopic virtual reality display. In ACM Transactions on Graphics (TOG) (Vol. 24, No. 3, pp. 894-903). ACM.

[6] Peterka, T., Kooima, R. L., Girado, J. I., Ge, J., Sandin, D. J., & DeFanti, T. A. (2007). Evolution of the VarrierTM Autostereoscopic VR Display: 2001-2007. In Proceedings of SPIE, the International Society for Optical Engineering (pp. 649004-1). Society of Photo-Optical Instrumentation Engineers.

[7] Schwerdtner, A., & Heidrich, H. (1998, January). Dresden 3D display (D4D). In Proc. SPIE (Vol. 3295, p. 203).

[8] Perlin, K., Paxia, S., & Kollin, J. S. (2000, July). An autostereoscopic display. In Proceedings of the 27th annual conference on Computer graphics and interactive techniques (pp. 319-326). ACM Press/Addison-Wesley Publishing Co.

[9] Peterka, T., Kooima, R. L., Girado, J. I., Ge, J., Sandin, D. J., Johnson, A., ... & DeFanti, T. A. (2007, March). Dynallax: solid state dynamic parallax barrier autostereoscopic VR display. In Virtual Reality Conference, 2007. VR'07. IEEE (pp. 155-162). IEEE.

[10] Peterka, T., Kooima, R. L., Sandin, D. J., Johnson, A., Leigh, J., & DeFanti, T. A. (2008). Advances in the dynallax solid-state dynamic parallax barrier autostereoscopic visualization display system. IEEE transactions on visualization and computer graphics, 14(3), 487-499.

[11] Mashitani, K., Hamagishi, G., Higashino, M., Ando, T., & Takemoto, S. (2004). Step barrier system multi-view glass-less 3-D display. Image, 1(2), 3.

[12] Smith, R. T., & Piekarski, W. (2008, January). Public and private workspaces on tabletop displays. In Proceedings of the ninth conference on Australasian user interface-Volume 76 (pp. 51-54). Australian Computer Society, Inc.

[13] Zhang, Q., & Kakeya, H. (2014). A high quality autostereoscopy system based on time-division quadplexing parallax barrier. IEICE Transactions on Electronics, 97(11), 1074-1080.

[14] Matusik, W., Forlines, C., & Pfister, H. (2008, May). Multiview user interfaces with an automultiscopic display. In Proceedings of the working conference on Advanced visual interfaces (pp. 363-366). ACM.

[15] W. (1998, May). Designing and building the pit: a head-tracked stereo workspace for two users. In 2nd International Immersive Projection Technology Workshop (pp. 11-12).

[16] Schreer, O., Feldmann, I., Atzpadin, N., Eisert, P., Kauff, P., & Belt, H. J. W. (2008). 3D presence-a system concept for multi-user and multi-party immersive 3D video conferencing.

[17] McGinity, Matthew, et al. "AVIE: a versatile multi-user stereo 360 interactive VR theatre." Proceedings of the 2007 workshop on Emerging displays technologies: images and beyond: the future of displays and interacton. ACM, 2007.

[18] Ehnes, Jochen, Christian Knopfle, and Matthias Unbescheiden. "The pen and paper paradigm-supporting multiple users on the Virtual Table." Virtual Reality, 2001. Proceedings. IEEE. IEEE, 2001.

[19] Kitamura, Yoshifumi, et al. "Interactive stereoscopic display for three or more users." Proceedings of the 28th annual conference on Computer graphics and interactive techniques. ACM, 2001.

[20] Kitamura, Yoshifumi, et al. "The illusionhole with polarization filters." Proceedings of the ACM symposium on Virtual reality software and technology. ACM, 2006.

[21] Nashel, A., & Fuchs, H. (2009, May). Random hole display: A non-uniform barrier autostereoscopic display. In 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video, 2009 (pp. 1-4). IEEE.

[22] Marbach, Jonathan. "Image blending and view clustering for multi-viewer immersive projection environments." Virtual Reality Conference, 2009. VR 2009. IEEE. IEEE, 2009.

[23] Marbach, Jonathan. "Gpu acceleration of stereoscopic and multi-view rendering for virtual reality applications." Proceedings of the 16th ACM Symposium on Virtual Reality Software and Technology. ACM, 2009.

[24] Marbach, Jonathan. Supporting multiple users in single-stereo-pair immersive virtual reality environments. Diss. University of Colorado at Boulder, 2010.

[25] Schulze, Jurgen P., et al. "Democratizing rendering for multiple viewers in surround VR systems." 3D User Interfaces (3DUI), 2012 IEEE Symposium on. IEEE, 2012.

[26] Lanman, D., Hirsch, M., Kim, Y., & Raskar, R. (2010). Content-adaptive parallax barriers: optimizing dual-layer 3D displays using low-rank light field factorization. ACM Transactions on Graphics (TOG), 29(6), 163.

[27] Little, G. R., Gustafson, S. C., & Nikolaou, V. E. (1994, April). Multiperspective autostereoscopic display. In Proc. SPIE (Vol. 2219, pp. 388-394).

[28] c. van berkel && J. A. Clarke, 1997, "Characterization and optimization of 3D-LCD Module design", Proc. SPIE, 3012, 179-186

[29] Van Berkel, C. (1999, May). Image preparation for 3D-LCD. In Proc. SPIE (Vol. 3639, No. 1, pp. 84-91).

[30] K. Matsumoto & T. Honda, 1997, "Research of 3D display using anamorphic optic", Proc. SPIE, 3012, 199-207

[31] Omura, K., Shiwa, S., & Miyasato, T. (1998). Lenticular autostereoscopic display system: multiple images for multiple viewers. Journal of the Society for Information Display, 6(4), 313-324.

[32] Eichenlaub, J. (1999, May). Multiperspective look-around autostereoscopic projection display using an ICFLCD. In Proc. SPIE (Vol. 3639, pp. 110-121).

[33] Son, J. Y., Shestak, S. A., Kim, S. S., & Choi, Y. J. (2001, June). Desktop autostereoscopic display with head tracking capability. In Proceedings of SPIE Vol. 4297, Stereoscopic Displays and Virtual Reality Systems VIII.

[34] Jeon, H. I., Jung, N. H., Choi, J. S., Kang, Y. S., Choi, S. H., Shin, S. H., & Son, J. Y. (2000). Super Multi-View 3-D Display System using Vibrating Scanner Array (ViSA). Journal of the Optical Society of Korea, 4(1), 37-42.

[35] Jeon, H. I., Jung, N. H., Choi, J. S., Jung, Y., Huh, Y., & Kim, J. S. (2001, June). Super multiview 3d display system using reflective vibrating scanner array. In Stereoscopic Displays and Virtual Reality Systems VIII (Vol. 4297, pp. 175-186).

[36] Lipton, L., & Feldman, M. (2002, May). A new autostereoscopic display technology: the SynthaGram. In Proc. SPIE (Vol. 4660, pp. 229-235).

[37] Matusik, W., & Pfister, H. (2004). 3D TV: a scalable system for real-time acquisition, transmission, and autostereoscopic display of dynamic scenes. ACM Transactions on Graphics (TOG), 23(3), 814-824.

[38] Nguyen, D., & Canny, J. (2005, April). MultiView: spatially faithful group video conferencing. In Proceedings of the SIGCHI conference on human factors in computing systems (pp. 799-808). ACM.

[39] Nguyen, D. T., & Canny, J. (2007, April). Multiview: improving trust in group video conferencing through spatial faithfulness. In Proceedings of the SIGCHI conference on Human factors in computing systems (pp. 1465-1474). ACM.

[40] Takaki, Y. (2005, January). Thin-type natural three-dimensional display with 72 directional images. In Proc. SPIE (Vol. 5664, pp. 56-63).

[41] Nakanuma, H., Kamei, H., & Takaki, Y. (2005). Natural 3D display with 128 directional images used for human-engineering evaluation. eye, 3, 3D.

[42] Kikuta, K., & Takaki, Y. (2007, February). Development of SVGA resolution 128-directional display. In Proc. SPIE (Vol. 6490, p. 64900U).

[43] Takaki, Y. (2009, February). Super multi-view display with 128 viewpoints and viewpoint formation. In Proc. SPIE (Vol. 7237, p. 72371T).

[44] Takaki, Y., Yokoyama, O., & Hamagishi, G. (2009, February). Flat panel display with slanted pixel arrangement for 16-view display. In Proc. SPIE(Vol. 7237, No. 723708, pp. 1-8).

[45] Takaki, Y., & Nago, N. (2010). Multi-projection of lenticular displays to construct a 256-view super multi-view display. Optics express, 18(9), 8824-8835.

[46] Surman, Phil, et al. "Head tracked single and multi-user autostereoscopic displays." Visual Media Production, 2006. CVMP 2006. 3rd European Conference on. IET, 2006.

[47] Brar, R. S., Surman, P., Sexton, I., Bates, R., Lee, W. K., Hopf, K., ... & Willman, E. (2010). Laser-based head-tracked 3D display research. Journal of Display Technology, 6(10), 531-543.

[48] Brar, Rajwinder Singh, et al. "Multi-user glasses free 3D display using an optical array." 2010 3DTV-Conference: The True Vision-Capture, Transmission and Display of 3D Video. IEEE, 2010.

[49] Kooima, Robert, et al. "A multi-viewer tiled autostereoscopic virtual reality display." proceedings of the 17th ACM Symposium on Virtual Reality Software and Technology. ACM, 2010.

[50] Sonoda, T., Yamamoto, H., & Suyama, S. (2011, March). A new volumetric 3-D display using multi-varifocal lens and high-speed 2-D display. In Proc. SPIE (Vol. 7863, No. 786322).

[51] Kim, S., Cao, X., Zhang, H., & Tan, D. (2012, May). Enabling concurrent dual views on common LCD screens. In proceedings of the SIGCHI conference on human factors in computing systems (pp. 2175-2184). ACM.

[52] Surman, Phil, et al. "Single and multi-user head tracked glasses-free 3D displays." 3DTV-Conference: The True Vision-Capture, Transmission and Dispaly of 3D Video (3DTV-CON), 2013. IEEE, 2013.

[53] Zang, Shang-Fei, et al. "A frontal multi-projection autostereoscopic 3D display based on a 3D-image-guided screen." Journal of Display Technology 10.10 (2014): 882-886.

[54] Hirabayashi, K., Tokoro, M., & Takaki, Y. (2014, March). Frameless multi-view display modules employing flat-panel displays for a large-screen autostereoscopic display. In IS&T/SPIE Electronic Imaging (pp. 901106-901106). International Society for Optics and Photonics.

[55] Jones, A., Unger, J., Nagano, K., Busch, J., Yu, X., Peng, H. Y., ... & Debevec, P. (2015, July). An automultiscopic projector array for interactive digital humans. In ACM SIGGRAPH 2015 Emerging Technologies (p. 6). ACM.

[56] A Universal Holographic Display for 3D Creators. (n.d.). Retrieved April 16, 2019, from https://lookingglassfactory.com/

[57] de la Re, A., Martorell, E., Camahort, E., & Abad, F. "Inexpensive

3D Stereo for Two Users Using a Single Display."

[58] Benton, S. A., Slowe, T. E., Kropp, A. B., & Smith, S. L. (1999, January). Micropolarizer-based multiple-viewer autostereoscopic display. In Proc. SPIE (Vol. 3639, pp. 76-83).

[59] Schmidt, A., & Grasnick, A. (2002, May). Multiviewpoint autostereoscopic dispays from 4D-Vision GmbH. In Electronic Imaging 2002 (pp. 212-221). International Society for Optics and Photonics.

[60] Matsushita, M., Iida, M., Ohguro, T., Shirai, Y., Kakehi, Y., & Naemura, T. (2004, November). Lumisight table: a face-to-face collaboration support system that optimizes direction of projected information to each stakeholder. In Proceedings of the 2004 ACM conference on Computer supported cooperative work (pp. 274-283). ACM.

[61] Kakehi, Y., Iida, M., Naemura, T., Shirai, Y., Matsushita, M., & Ohguro, T. (2005). Lumisight table: An interactive view-dependent tabletop display. IEEE Computer Graphics and Applications, 25(1), 48-53.

[62] Kakehi, Y., Hosomi, T., Iida, M., Naemura, T., & Matsushita, M. (2006, January). Transparent tabletop interface for multiple users on lumisight table. In Horizontal Interactive Human-Computer Systems, 2006. TableTop 2006. First IEEE International Workshop on (pp. 8-pp). IEEE.

[63] Jorke, H., & Fritz, M. (2006, February). Stereo projection using interference filters. In Proc. SPIE (Vol. 6055, p. 60550G).

[64] Jorke, H., Simon, A., & Fritz, M. (2008, May). Advanced stereo projection using interference filters. In 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video, 2008 (pp. 177-180). IEEE.

[65] Jorke, H., Simon, A., & Fritz, M. (2009). Advanced stereo projection using interference filters. Journal of the Society for Information Display, 17(5), 407-410.

[66] Simon, A., Prager, M. G., Schwarz, S., Fritz, M., & Jorke, H. (2010). Interference-filter-based stereoscopic 3D LCD. Journal of Information Display, 11(1), 24-27.

[67] Hamada, T., Nagano, K., & , T. U. A. S. (2010, April). Scritter. A multiplexed image system for a public screen. In Proceedings of Virtual Reality International Conference (VRIC) Laval Virtual ReVolution 2010 (pp. 321-323).

[68] Nagano, K., Utsugi, T., Hirano, M., Hamada, T., Shirai, A., & Nakajima, M. (2010, July). A new multiplex content displaying system compatible with current 3d projection technology. In ACM SIGGRAPH 2010 Posters (p. 79). ACM.

[69] Nagano, K., Utsugi, T., Yanaka, K., Shirai, A., & Nakajima, M. (2011, December). ScritterHDR: multiplex-hidden imaging on high dynamic range projection. In SIGGRAPH Asia 2011 Posters (p. 52). ACM.

[70] Kim, J., Kim, Y., Hong, J., Park, G., Hong, K., Min, S. W., & Lee, B. (2011). A full-color anaglyph three-dimensional display system using active color filter glasses. Journal of Information Display, 12(1), 37-41.

[71] Simon, A., & Jorke, H. (2011, June). 25.1: Interference Filter System for High-Brightness and Natural-Color Stereoscopic Imaging. In SID Symposium Digest of Technical Papers (Vol. 42, No. 1, pp. 317-319). Blackwell Publishing Ltd.

[72] Kakeya, H., & Kodaira, H. (2012, March). Full color stereoscopy with little flicker at low refresh rate by time-division multiplexing anaglyph. In Proc. SPIE (Vol. 8288, p. 82880K).

[73] Zhang, Q., & Kakeya, H. (2013, March). An autostereoscopic display system with four viewpoints in full resolution using active anaglyph parallax barrier. In Proc. SPIE (Vol. 8648, p. 86481R).

[74] Gaudreau, J. E. (2012, March). Full-resolution autostereoscopic display using an all-electronic tracking/steering system. In Stereoscopic Displays and Applications XXIII (Vol. 8288).

[75] Littfass, Y., Koide, Y., Suzuki, H., & Shirai, A. (2014, April). Scritter to 1p2x3D: application development using multiplex hiding imaging technology. In Proceedings of the 2014 Virtual Reality International Conference (p. 21). ACM.

[76] Suzuki, H., Hsieh, R., & Shirai, A. (2014, July). ExPixel: PixelShader for multiplex-image hiding in consumer 3D flat panels. In ACM SIGGRAPH 2014 Posters (p. 63). ACM.

[77] What is the MultiView feature? (n.d.). Retrieved July 10, 2018, from https://us.en.kb.sony.com/app/answers/detail/a_id/37101/ /what-is-the-simulview-feature

[78] Suzuki, H., Littfass, Y., Hsieh, R., Taguchi, H., Wataru, F., Koide, Y., & Shirai, A. (2014, April). FamiLinkTV: expanding the social value of the living room with multiplex imaging technology. In Proceedings of the 2014 Virtual Reality International Conference (p. 38). ACM.

[79] Agrawala, Maneesh, et al. "The two-user Responsive Workbench: support for collaboration through individual views of a shared space." Proceedings of the 24th annual conference on Computer graphics and interactive techniques. ACM Press/Addison-Wesley Publishing Co., 1997.

[80] Moore, J. R., Dodgson, N. A., Travis, A. R., & Lang, S. R. (1996, January). Time-multiplexed color autostereoscopic display. In PROCEEDINGS-SPIE THE INTERNATIONAL SOCIETY FOR OPTICAL ENGINEERING (pp. 10-19). SPIE INTERNATIONAL SOCIETY FOR OPTICAL.

[81] Dodgson, N. A., Moore, J. R., & Lang, S. R. (1999, September). Multi-view autostereoscopic 3D display. In International Broadcasting Convention (Vol. 2, pp. 497-502).

[82] Dodgson, N. A., Moore, J. R., Lang, S. R., Martin, G., & Canepa, P. (2000). A time-sequential multi-projector autostereoscopic display. Journal of the Society for Information Display, 8(2), 169-176.

[83] Dodgson, N. A., Moore, J. R., Lang, S. R., Martin, G. J., & Canepa, P. M. (2000, May). 50-in. time-multiplexed autostereoscopic display. In Electronic Imaging (pp. 177-183). International Society for Optics and Photonics.

[84] Shoemaker, G. (2000, April). Supporting private information on public displays. In CHI'00 Extended Abstracts on Human Factors in Computing Systems (pp. 349-350). ACM.

[85] Shoemaker, G. B., & Inkpen, K. M. (2001, March). Single display privacyware: augmenting public displays with private information. In Proceedings of the SIGCHI conference on Human factors in computing systems (pp. 522-529). ACM.

[86] StereoGraphics. (2017, March 20). Retrieved July 12, 2018, from https://en.wikipedia.org/wiki/StereoGraphics

[87] Blom, Kristopher, Gary Lindahl, and Carolina Cruz-Neira. "Multiple active viewers in projection-based immersive environments." Immersive Projection TechnologyWorkshop (2002).

[88] Froehlich, B., Hoffmann, J., Klueger, K., & Hochstrate, J. (2004, May). Implementing multi-viewer time-sequential stereo displays based on shuttered lcd projectors. In 4th Immersive Projection Technology Workshop, Ames, Iowa (May 2004).

[89] Cossairt, O., Travis, A. R., Moller, C., & Benton, S. A. (2004, May). Novel view sequential display based on DMD technology. In Electronic Imaging 2004 (pp. 273-278). International Society for Optics and Photonics.

[90] McDowall, I. E., Bolas, M. T., Hoberman, P., & Fisher, S. S. (2004, August). Snared illumination. In ACM SIGGRAPH 2004 Emerging

technologies (p. 24). ACM.

[91] Blach, R., Bues, M., Hochstrate, J., Springer, J., & Froehlich, B. (2005, March). Experiences with multi-viewer stereo displays based on lc-shutters and polarization. In Proceedings of IEEE VR workshop: Emerging display technologies.

[92] Froehlich, Bernd, et al. Implementing multi-viewer stereo displays. (2005).

[93] Kupiec, S., Markov, V., Hopper, D., & Saini, G. (2008, February). Multiview multiperspective time multiplexed autostereoscopic display. In Proc. SPIE (Vol. 6803, p. 68030N).

[94] Mistry, P. (2009, December). ThirdEye: a technique that enables multiple viewers to see different content on a single display screen. In ACM SIGGRAPH ASIA 2009 Posters (p. 29). ACM.

[95] Brar, Rajwinder Singh, et al. "Helium3D: a laser-based 3D display with'3D+'Capability." Visual Media Production (CVMP), 2010 Conference on. IEEE, 2010.

[96] Surman, Phil. "Laser-based multi-user multi-modal 3D displays." 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON), 2011. IEEE, 2011.

[97] Akşit, K., Ölçer, S., Erden, E., Kishore, V. C., Urey, H., Willman, E., ... & Surman, P. (2011, May). Light engine and optics for HELIUM3D auto-stereoscopic laser scanning display. In 3DTV Conference: The True Vision-Capture, Transmission and Display of 3D Video (3DTV-CON), 2011 (pp. 1-4). IEEE.

[98] Kulik, A., Kunert, A., Beck, S., Reichel, R., Blach, R., Zink, A., & Froehlich, B. (2011). C1x6: a stereoscopic six-user display for co-located collaboration in shared virtual environments. ACM Transactions on Graphics (TOG), 30(6), 188.

[99] Beck, Stephan, et al. "Immersive group-to-group telepresence." IEEE Transactions on Visualization and Computer Graphics 19.4 (2013): 616-625.

[100] Lissermann, R., Huber, J., Schmitz, M., Steimle, J., & Mühlhäuser, M. (2014, April). Permulin: mixed-focus collaboration on multi-view tabletops. In Proceedings of the 32nd annual ACM conference on Human factors in computing systems (pp. 3191-3200). ACM.

[101] Hayashi, A., Kometani, T., Sakai, A., & Ito, H. (2010). A 23-in. full-panel-resolution autostereoscopic LCD with a novel directional backlight system. Journal of the Society for Information Display, 18(7), 507-512.

[102] Liou, J. C., & Chen, F. H. (2012, March). A novel time-multiplexed autostereoscopic multi-view full resolution 3D display. In Proc. SPIE (Vol. 8288, p. 82880U).

[103] Geng, J. (2014, March). Design of a single projector multiview 3D display system. In Proc. of SPIE Vol (Vol. 8979, pp. 89790K-1).

[104] Koutaki, Gou. "Binary continuous image decomposition for multiview display." ACM Transactions Graphics (TOG) 35.4 (2016): 69.

[105] Barnum, P. C., Narasimhan, S. G., & Kanade, T. (2010, July). A multi-layered display with water drops. In ACM Transactions on Graphics (TOG) (Vol. 29, No. 4, p. 76). ACM.

[106] Sullivan, A. (2003, May). 58.3: A Solid-state Multi-planar Volumetric Display. In SID symposium digest of technical papers (Vol. 34, No. 1, pp. 1531-1533). Blackwell Publishing Ltd.

[107] Favalora, Gregg E., et al. "Volumetric three-dimensional display system with rasterization hardware." Photonics West 2001-Electronic Imaging. International Society for Optics and Photonics, 2001.

[108] Otsuka, Rieko, Takeshi Hoshino, and Youichi Horry. "Transpost: All-around display system for 3D solid image." Proceedings of the ACM symposium on Virtual reality software and technology. ACM, 2004.

[109] Jones, A., McDowall, I., Yamada, H., Bolas, M., & Debevec, P. (2007, August). Rendering for an interactive 360 light field display. In ACM Transactions Graphics (TOG) (Vol. 26, No. 3, p. 40). ACM.

[110] Eitoku, Shinichiro, Tomohiro Tanikawa, and Yasuhiro Suzuki. "Display composed of water drops for filling space with materialized virtual three-dimensional objects." Virtual Reality Conference, 2006. IEEE, 2006.

[111] Bimber, Oliver, et al. "The virtual showcase." ACM SIGGRAPH 2006 Courses. ACM, 2006.

[112] Nayar, S. K., & Anand, V. N. (2006, July). 3d volumetric display using passive optical scatterers. In ACM SIGGRAPH 2006 Sketches (p. 106). ACM.

[113] Kimura, H., Uchiyama, T., & Yoshikawa, H. (2006, July). Laser produced 3D display in the air. In ACM SIGGRAPH 2006 Emerging technologies (p. 20). ACM.

[114] Cossairt, O. S., Napoli, J., Hill, S. L., Dorval, R. K., & Favalora, G. E. (2007). Occlusion-capable multiview volumetric three-dimensional display. Applied Optics, 46(8), 1244-1250.

[115] Gocho, S., Yamanouchi, T., Hilano, T., & Yanaka, K. (2016, November). Four-plane depth-fused 3D display using single flat panel display. In SIGGRAPH ASIA 2016 Posters (p. 13). ACM.

[116] Suyama, S., Ohtsuka, S., Takada, H., Uehira, K., & Sakai, S. (2004). Apparent 3-D image perceived from luminance-modulated two 2-D images displayed at different depths. Vision research, 44(8), 785-793.

[117] Wetzstein, G., Lanman, D., Heidrich, W., & Raskar, R. (2011, August). Layered 3D: tomographic image synthesis for attenuation-based light field and high dynamic range displays. In ACM Transactions on Graphics (ToG) (Vol. 30, No. 4, p. 95). ACM.

[118] Lanman, D., Wetzstein, G., Hirsch, M., Heidrich, W., & Raskar, R. (2011). Polarization fields: dynamic light field display using multi-layer LCDs. ACM Transactions on Graphics (TOG), 30(6), 186.

[119] Wetzstein, G., Lanman, D., Hirsch, M., & Raskar, R. (2012). Tensor displays: compressive light field synthesis using multilayer displays with directional backlighting.

[120] Chen, R., Maimone, A., Fuchs, H., Raskar, R., & Wetzstein, G. (2014). Wide field of view compressive light field display using a multilayer architecture and tracked viewers. Journal of the Society for Information Display, 22(10), 525-534.

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