Parallel Optics in Waveguide Displays: a Flat Panel Autostereoscopic Display

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***Abstract*—In order to demonstrate the Wedge as a parallel optic we have built a flat panel multi-projector autostereoscopic 3D display. The bulk otherwise inherent in such displays has been eliminated by use of a wedge-shaped light-guide. Two 280mm (11”) diagonal VGA resolution views were formed on a 406mm (16”) diagonal screen by pointing a pair of LED-illuminated pico-projectors measuring 115x50x22mm into the 20 mm thick input face of a 710mm long acrylic wedge. Distortions introduced by the Wedge were reduced to less than 2% by predistortion algorithms and distortion between views was less than 0.4%. Between the projectors was placed an infra-red camera which imaged objects placed directly in front of the 3D screen.**

***Index Terms*—flat panel, 3D display, multiprojector, interactive.**

I. Introduction

Autostereoscopic displays are designed to give the viewer the illusion of a 3D object or scene without the use of any headgear [1], [2]. This is useful in a number of situations; where a headset or glasses are not feasible or are impractical, such as cockpit displays or mobile displays; or where there are large numbers of passing viewers, such as advertising displays.

Autostereoscopic displays function by subdividing the viewing space of the display into multiple ‘viewing windows’ and then presenting a different 2D projection to each window [1], [3]; see Fig. 1. There have been numerous methods proposed for creating such displays, and they can be broadly broken down into three categories; time-sequential, view-sequential and multiprojector [3].

In recent years, research in the field of 3D displays has focused heavily on time-sequential autostereoscopic display systems [4]; utilizing single, high-speed display devices to scan through all of the desired perspective views every frame. Such systems include many of those developed at Cambridge University [1], [3], [4], based on the time-sequential principle described by Travis [5].

Multiprojector systems operate by using a single projector to display each perspective view. This means that images are bright and can be displayed at the display’s native resolution and color depth, without compromising the frame rate.

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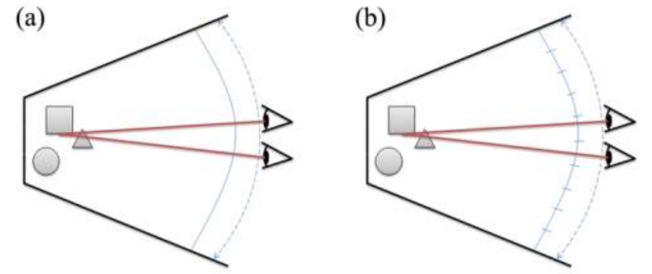

Fig. 1. (a) A real scene as seen by the viewer; an infinite number of perspectives are viewable. (b) To make it feasible to reproduce the scene via a practical display the number of possible perspectives is reduced, with different perspectives visible in each ‘viewing window’; as described in [3].

The main issues that affect multiprojector displays are the cost and size of the display devices and the difficulty in aligning them. Multiprojector systems also suffer from the high data bandwidths normally associated with time-sequential displays [4].

In the past view-sequential displays have been the focus of much research; subdividing the horizontal resolution of the display to interlace multiple perspectives. This was a result of the advances in 2D display devices; being better suited to this method, displays could be constructed using only off-the-shelf components [4]. Only recently have display devices, drive electronics and computer graphics hardware advanced to the state that larger multiprojector and time-sequential systems are feasible to construct.

The use of an optical Wedge means that a flat panel, multiprojector display can now be constructed.

II. Principles of 3D

The principle behind the constructed display is similar to that behind the Cambridge displays [1], [3], [5], [6]. If a point source is placed behind a lens then moved off axis the image of that source moves proportionally. If two image sources are used projecting perspectives that match the source position, and arranged such that each image is projected into one of the viewer’s eyes, the viewer will perceive a 3D image by means of retinal, or binocular, disparity [7]; see Fig. 2.

The Cambridge displays [1], [3], [5], [6] achieve this effect by sequentially projecting each perspective through a transmissive Ferroelectric Liquid Crystal Display (FLCD) optical shutter; mimicking multiple image sources. The multiprojector display constructed operates by replacing the point sources with individual pico-projectors.

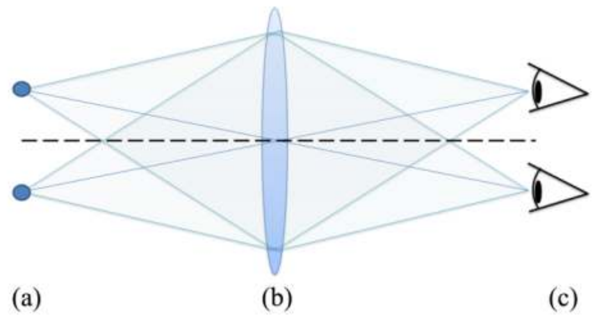

Fig. 2. Illustration of the principle of the 3D display constructed. (a) Denotes two point image sources; (b) shows a thin lens; and (c) depicts the eyes of the viewer, with one perspective visible to each eye.

III. THE WEDGE

The Wedge is a waveguide comprised of a tapered sheet of optically transparent material; PMMA or Acrylic would be typical. When a ray is injected into the entrance of the Wedge it is internally reflected at each material-air interface. Once the ray reaches the critical angle of the material it exits the Wedge; see Fig. 3(a). However, note that the exit angle of the Wedge is small; therefore a turning film is required to turn the rays towards being perpendicular with the exit surface. This results in at least one extra air-material interface within any Wedge-based system, and thus a slight decrease in contrast.

The Wedge behaves like a lens. This is because if a point source is placed at the entrance, each ray is arranged such that it exits at the critical angle of the material and at a specific point on the Wedge exit surface. As a result all of the rays exit parallel to one another. This behavior is analogous to that of a simple lens; see Fig. 4.

As a consequence of being able to control the point at which the ray exits on the Wedge surface via the entrance angle, placing a projector at the entrance face, and a diffusing screen on the exit surface, produces a flat panel rear projection display; as depicted in Fig. 3(b). Further, as the Wedge is a reversible optical system, placing a camera at the entrance face yields a flat panel imaging system.

Reducing the projection volume in most systems would involve folding the projection volume using plane mirrors. However, the use of a Wedge optical waveguide allows this projection volume to be compressed into a flat panel.

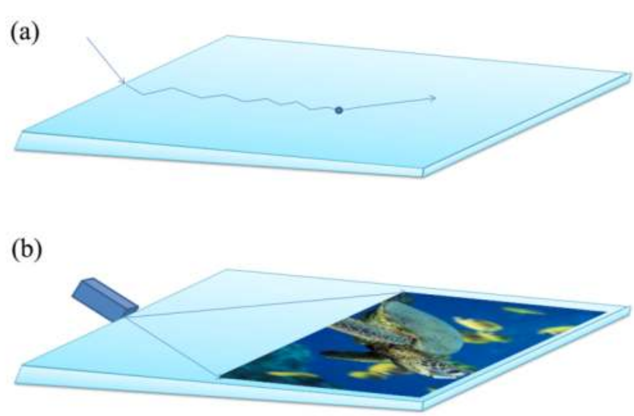

Fig. 3. (a) Shows the principle behind the Wedge; a ray is injected at the entrance face, and exits at the surface. (b) Shows how a Wedge can be used as a flat panel display using a projector.

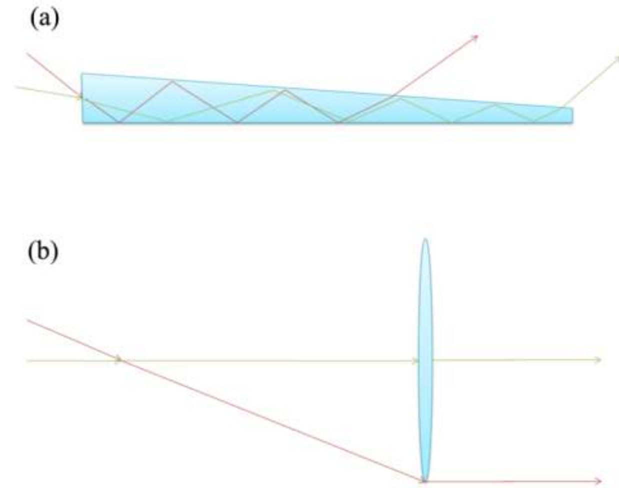

Fig. 4. Analogous Wedge and lens behavior; (a) shows the Wedge collimating rays that have differing entrance angles, (b) shows a simple lens behaving in a similar manner.

IV. THE WEDGE AS AN AUTOSTEREO DISPLAY

The principle by which stereo parallax is achieved, described in section II and illustrated in Fig. 2, is well understood. The principle of a waveguide display is also well understood. The utilization of a Wedge display as an autostereoscopic display requires multiple images to be projected from the display surface at different angles. This can be achieved in a similar manner to that illustrated in Fig. 2; separating the image sources, as well as tilting their optical axes, results in an angular separation of the projected images at the Wedge exit face. This idea is shown in Fig. 5; two off-axis projectors produce output images on the same surface, but at different angles.

It is evident that this method will introduce complementary keystone distortion into both views; both images are being projected onto the exit surface off-axis.

As described in Fig. 4, the rays injected into a Wedge from a point source become collimated at the output face. Therefore

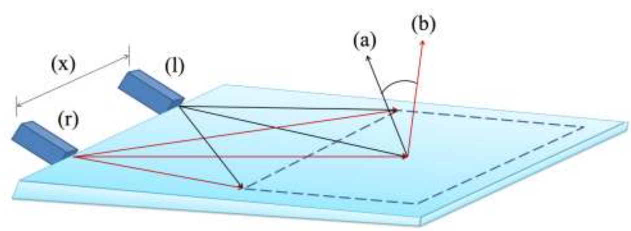

Fig. 5. Producing stereo parallax using a Wedge projection display in a multiprojector system. The ray (a) is associated with projector (l), and the ray (b) corresponds to projector (r). The small angle subtended between rays (a) and (b) is related to the projector separation (x); this means that for any required image separation a projector separation can be calculated. Note that the projectors (l) and (r) will need to present the right and left eye images respectively; the images are ‘reversed’ in the same way as appears in Fig. 2.

if a viewer was to look at the idealized Wedge projection system shown in Fig. 5 they would simply see two ‘bright spots’ appear at the exit face. This is because only a very narrow region of the collimated image is visible to each eye. To correct this, a screen assembly needs to be added.

To enable a viewer to see both images in their entirety requires the collimated rays to be focused into the viewer’s eyes. This can be achieved by adding a Fresnel lens to the system, on the exit face of the Wedge. This does however mean that if the viewer is not exactly in the correct position, the stereoscopic effect would collapse. There is also no compensation for variations in viewers’ inter-ocular separation so many people may not be able to observe a stereoscopic effect at all.

To account for this, a narrow angle diffuser can be included in the ‘screen’ assembly. This gives a level of tolerance for both horizontal and vertical viewer position, as well as variation in viewers’ inter-ocular separation. This increases the horizontal and vertical viewing angles. It should be noted that the horizontal diffusion angle should be less than the angular separation of the two images, so as to prevent cross-talk between views.

V. Optical Simulation

An optical computer simulation was set up using the profile data for the Wedge to be used within the functioning system. The aim of this was to demonstrate the parallax effect achieved using this multiprojector set up, as well as offer some predictions about the behavior of the assembled system.

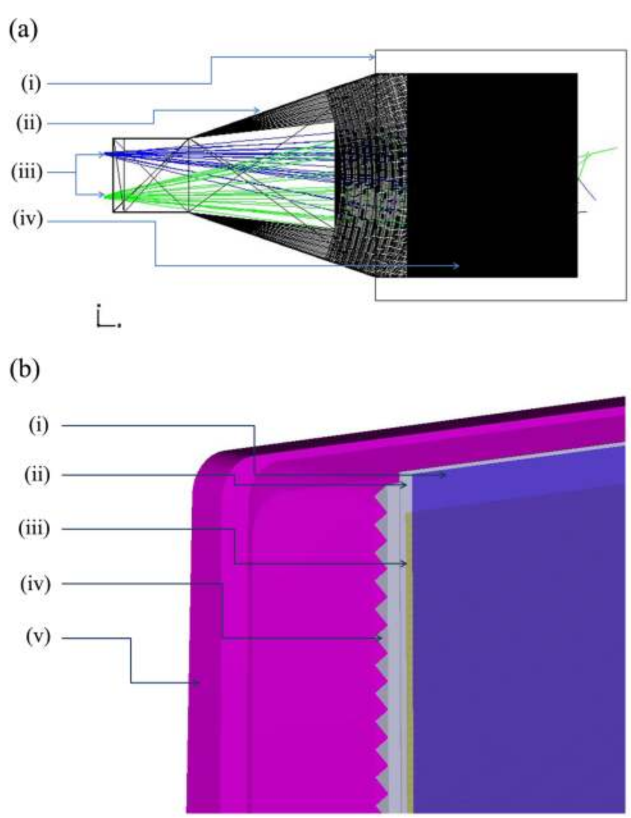

Fig. 6. Two images showing the computer model used to simulate the proposed system.

The modeled screen assembly consisted of a Fresnel lens of an appropriate focal length and a vertical one-dimensional diffuser, modeled using a fine pitched lenslet array. The simulation also included a turning film as required by the Wedge (described in section III). The simulation configuration is shown in Fig. 6.

From Fig. 6(a), (i) denotes the off-screen detector plane, (ii) denotes the Wedge model constructed from CAD data, (iii) shows the two separated point sources, and (iv) represents the screen assembly used, which is further described in Fig. 6(b).

In Fig. 6(b), (i) denotes the detector plane on the image plane, (ii) represents the Fresnel lens used to focus the collimated Wedge output, (iii) shows a fine horizontal lenslet array used to mimic a vertical diffuser, (iv) denotes the turning film required by the Wedge, and (v) denotes the Wedge panel itself.

The results of the simulation are shown in Fig. 7. The traces produced by the two detectors have been mapped onto the model’s detector surfaces, and the ray trace data has been included. This model demonstrates that the image brightness at the screen should appear uniform, and also shows the formation of the viewing windows described previously.

From this theoretical display, we can now move on to describe the construction of a practical display, and evaluate its’ performance.

VI. System Design

The following section describes the main components of the constructed system and the method in which they are utilized.

A. Projectors

The projectors used within this system are ‘off-the-shelf’ components. As a result they required no modification. Each projector consists of an LED light source; an LCoS display

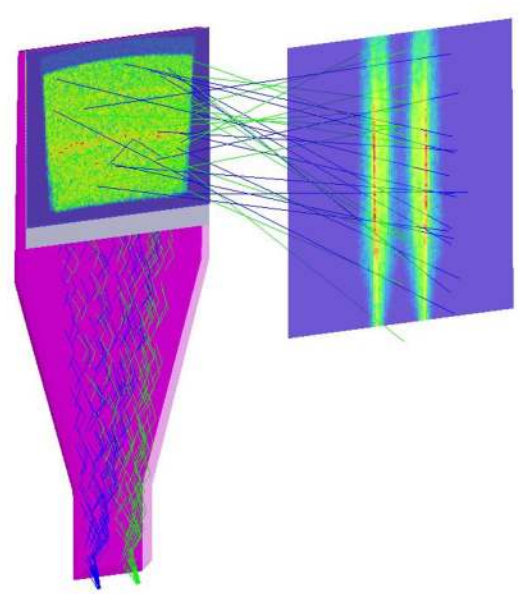

Fig. 7. The results of ray tracing the system modeled in Fig. 6. The image plane detector demonstrates an even illumination, as well as the Wedge distortions introduced. The focal plane detector shows the viewing window separation with no horizontal diffusion. 100,000 rays were traced.

element (Liquid Crystal on Silicon); projection optics and drive electronics. The projectors accept video input via a standard VGA connector up to WXGA resolution (1280x768 pixels); however note that the native resolution of the LCoS display device is only VGA (640x480 pixels). The device is capable of a 60Hz refresh rate [8].

These devices were supplied with a VGA input signal (640x480 pixels) at a refresh rate of 60Hz, and color depth of 24 bits; this corresponds to 8 bits for each RGB component. The color data was transmitted using a standard 32 bit video format (padded with non-color information); this corresponds to a data rate of approximately 0.59 Gbits/s per video signal; approximately 1.2Gbits/s total.

One advantage of using pico-projectors is that they are designed to be very small; the projectors used were 115x50x22mm [8]. As a result the devices compromise on resolution and frame rate; the projector used by Møller and Travis [4] was capable of 800fps at 800x600 pixels resolution (SVGA). The device was, however, housed in a 1x1x1m casing.

B. *The Wedge*

The Wedge component used had a screen size of 244x325mm (406mm (16”) diagonal, 4:3 aspect ratio) approximately with a throw distance of 470mm, resulting in a projected image size of 178x229mm (7x9”). The border around the image was masked by the screen assembly.

The ideal screen for the system consists of a non-symmetrical, ‘top-hat’ diffuser with strong vertical diffusion and a horizontal diffusion angle equal to the angle subtended by the two image focal points. This means that there would be a large range of vertical viewing positions, the adjacent viewing windows would abut, and there would be some horizontal tolerance for changes in position and viewer interocular separation.

The screen fitted to the exit face of the Wedge consisted of a Fresnel lens with a focal length of 350mm (13.8”) and a glass infra-red (IR) waveguide with a 5° diffuser bonded to the outermost surface; see Fig. 8. The waveguide takes advantage of the unique properties of the Wedge; allowing the system to be simultaneously used as an imaging system and a display.

The narrow angle diffuser that forms part of the IR waveguide also acted as the image diffuser. While producing a small vertical viewing window it preserved image brightness as well as touch localization.

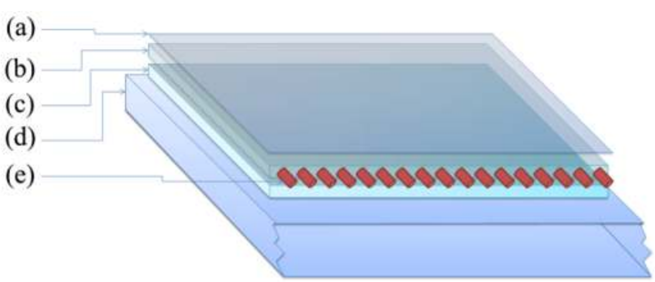

Fig. 8. (a) Top diffuser bonded to infrared waveguide; this is required to ‘bleed’ light out of waveguide (b). (b) IR waveguide made from a glass plate. (c) Fresnel lens, which is a part of the Wedge projection system, rather than the IR imaging system. (d) Wedge panel which collects backscattered light from touch events as well as operating as a projection display. (e) Array of IR LEDs. Note that there is an air gap between (b) and (c), and (c) and (d). The Wedge turning film has been omitted for clarity.

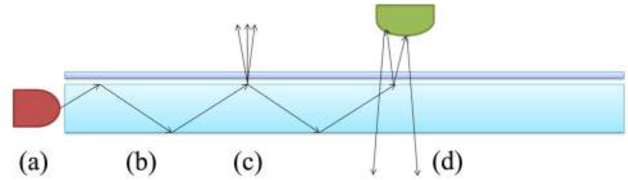

Fig. 9. Diagram showing the behavior of the imaging system utilized to detect touch events. (a) denotes the IR LED array from Fig. 8. (b) shows the rays being totally internally reflected along the waveguide. (c) illustrates that the internal reflections are ‘frustrated’ by the narrow diffusing film; a small portion of the light is diffused out from the screen, illuminating objects. (d) shows an illuminated object back-scattering rays, which are captured by the Wedge and transmitted back to the camera shown in Fig. 10.

C. *Touch Event Detection*

The screen assembly described in Fig. 8 contains several components of both the projection and imaging systems. The imaging system components include the array of IR LEDs, the glass IR waveguide and the narrow angle diffuser bonded to this waveguide.

The imaging system behaves in the manner shown in Fig. 9; light is totally internally reflected along the glass waveguide. As one surface of the waveguide has been made diffuse, a small proportion of light ‘bleeds’ out at each interaction with that interface, illuminating objects in front of the screen.

To utilize the Wedge as an imaging system a Firewire camera was placed between the two pico-projectors using a folding prism, as shown in Fig. 10. The camera lens was fitted with an IR filter matching the peak wavelength of the LEDs used; approximately 880nm. The result of using the folding prism was that not the entire exit surface of the Wedge was visible, resulting in a smaller active area.

Fig. 11 shows an image captured using the IR camera system, showing several simultaneous touch events. This input stream is subsequently passed through a threshold filter, and a ‘blob’ detection algorithm is applied to extract the centre point data for each touch event.

Fig. 10. Camera and projectors at the Wedge entrance face.

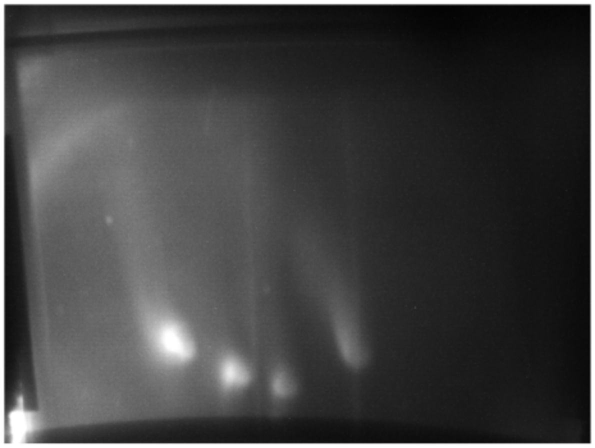

Fig. 11. Raw image of touch events imaged through the Wedge and screen assembly.

D. Computer Hardware and Graphics Rendering

The computer used was a P4-based system with a four output, dual GPU graphics card with 1GB of on-board memory. The use of such a powerful graphics device shifted a significant load from the main CPU, which made the process of generating stereo graphics in real time less CPU-intensive. Fig. 12 shows some of the images used to test the system.

The graphics in Fig. 12(a) were generated using a crossed axis, non-perpendicular camera model. This means that the image planes of the cameras were not perpendicular to the camera axes, but rather were coincident with one another (Fig. 13). This means that there was no significant relative geometric distortion between views associated with this method. The image in Fig. 12(b) was generated using the parallel axis camera method described by McAllister [7], with the interaxial separation being user-definable and adjustable in real time.

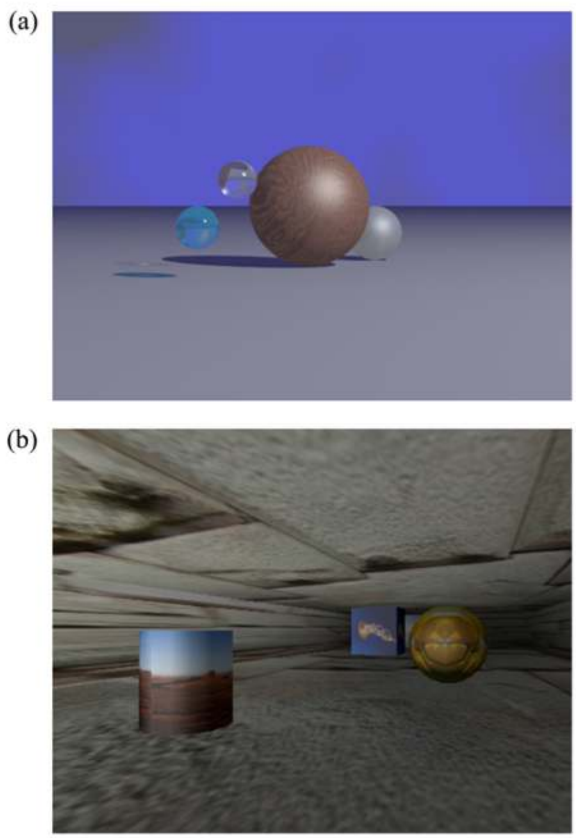

Fig. 12. (a) Frame from a pre-rendered video file. (b) Image capture from a real-time generated interactive environment built within a pre-existing graphical programming tool.

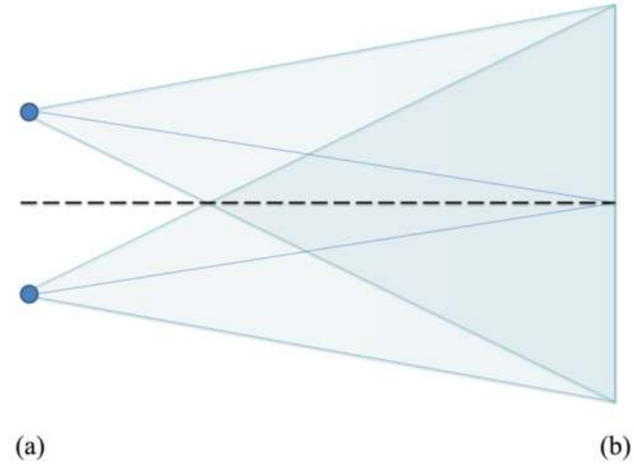

Fig. 13. Camera model used to render the image in Fig. 12(a). (a) denotes the stereo camera pair, and (b) represents the common image plane (also called the stereo window). Note that the camera axes are not perpendicular to the image plane.

A significant problem encountered during initial construction of the display was the poor image alignment obtained solely via mechanical positioning of the projectors.

As the projectors are both off of the Wedge axis they exhibited horizontal keystone distortion; this effect was exacerbated by the image distortions inherent in the Wedge itself.

To correct the keystone distortion in the images a software

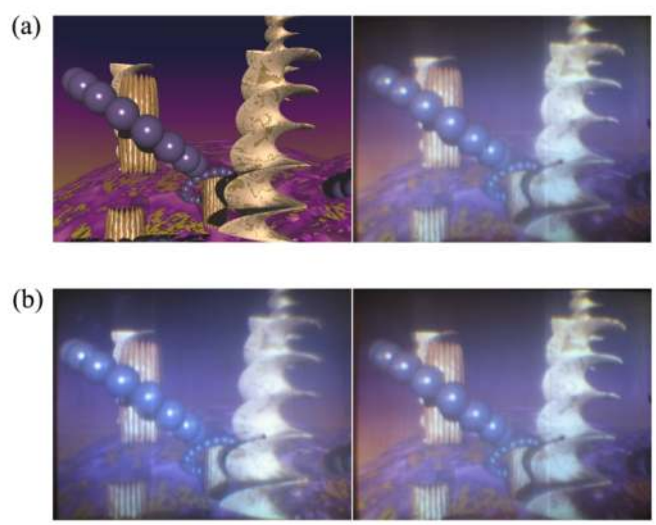

Fig. 14. Screen images from the constructed display. (a) Shows the left channel source image (left) and displayed image (right), and (b) shows a right-left stereo pair of images captured, arranged for cross-viewing.

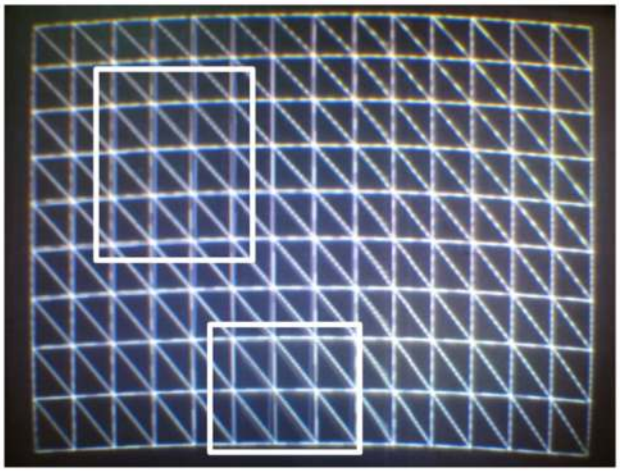

Fig. 15. The calibration grid as viewed on the assembled display. The two regions highlighted show where there is some relative distortion between the two perspective views.

based method was devised. Each perspective view was mapped onto a rectangular grid which was rotated in 3D space to allow both images to be aligned on the screen by manually adjusting the grid corner points. This sacrificed some image resolution but greatly aided the 3D effect by making the disparity between the views more uniform.

VII. 3D IMAGE QUALITY

Fig. 14 shows a set of images as produced by the display. Fig. 14(a) shows the source image, left, for the left eye channel, and the same image projected through the display, right. (b) shows both the right eye channel (left) and left eye channel (right) arranged for crossed stereo viewing.

The images in Fig. 14(a) give a qualitative comparison of the image quality of the display, whereas Fig. 14(b) is aimed at showing that the degradation in the images projected does not have a large effect on the perceived 3D effect. The images also show some ghosting and other minor artifacts that are caused by the Wedge.

The image in Fig. 15 shows a calibration grid that was incorporated into the display’s operating software. This image also illustrates the radial distortions introduced by the Wedge. It was noted that this curvature had little effect on the perceived stereoscopic effect, but it did prove ‘distracting’ when viewing images that contained straight horizontal lines.

Using the calibration grid shown in Fig. 15 measurements were taken to establish how well the pixels within one perspective view matched to the ‘sister’ pixels within the other view. A relative distortion of approximately 2 pixels was measured; ideally both images would be aligned exactly. This approximates to a 0.31% error in horizontal position and a 0.42% error in vertical position. This distortion is visibly noticeable when viewing the calibration grid, but does not appear to have any detrimental effects on the 3D image. Determining the effect this distortion has on stereopsis should be the subject of further investigation.

The residual distortion in each view was quantified by minimizing the distortion value against a scalable rectilinear grid of points with a variable magnification in each axis. This method produced a value of approximately 9 pixels for both eye perspectives. This translates to 1.4% horizontal and 1.9% vertical distortion. This distortion could be minimized by correcting the images to account for the distortions inherent in the Wedge (i.e. barrel distortion); this should also be a topic of further investigation.

The contrast ratio of the projectors was measured to be approximately 30.8, using the ANSI method. The same method was used to measure the contrast of the system omitting the Wedge component; a value of approximately 28.5. The contrast ratio of the whole system was subsequently measured to be 12.9; this implies a Wedge-screen assembly contrast of approximately 22.4. It can be seen that the Wedge itself is the limiting factor within the system, with an implied contrast ratio of 23.9.

The two projectors were measured to match in brightness to within 7.5%. The two views also have an average cross-talk of 7.6% (6.7% for the left view and 8.6% for the right); this infers that the two views have an average extinction ratio of 4.7 (4.69 for the left view and 4.67 for the right). The extinction ratio is defined as the ratio of the luminance of an image seen by one eye and its ghost as seen by the other eye [7]. As the extinction ratio decreases, the crosstalk between the perspective views increases.

VIII. SCALABILITY AND EXPANDABILITY OF THE SYSTEM

The system is easily scalable due to the use of the Wedge component. Increasing the size of the Wedge results in an increase in image size because the Wedge acts like a waveguide [4]. This means that the system is potentially scalable to any practical screen diagonal.

The Wedge used within the system constructed had a narrow entrance window; a result of it being designed for a single projector. As a consequence of the profile of the Wedge, manufacturing a panel with a wider entrance face is relatively simple, and could allow up to approximately six pico-projectors to be used simultaneously using the same Wedge variant employed in the described system.

The use of extra pico-projectors would benefit the system, as currently the range of horizontal viewing position which gives a 3D effect is very narrow. Increasing the horizontal viewing space should be of prime importance in any further development; adding extra perspectives may be an easy method of accomplishing this. However, the effect this would have on the required computational resources of the system would also need to be considered.

IX. DISCUSSION

The use of an optical Wedge means that this type of 3D display is potentially thinner than many other types of multiperspective displays; approximately 33mm thick for a 1270mm (50 inch) diagonal panel; a diagonal to thickness ratio of approximately 42.3. Touch interactivity is also a feature that is distinctly lacking in other types of autostereo display.

Different variants of the Wedge can also be folded, meaning that the entire front surface is active without the ‘dead area’ that is present on the Wedge used in the described system. This potentially means that a display could be constructed with no screen surround, which may benefit the 3D effect by reducing the conflicting cues [7] produced by having a stark border around the image.

Areas of further investigation include the image distortions introduced by the Wedge and their rectification; quantifying the perceived depth of the image and increasing the number of perspective views and overall size of the viewing space.
Correcting for the Wedge distortion is important as it may have an effect on viewer stereopsis; it was noted that the curvature of the image was distracting where images consisting of straight horizontal lines were displayed.

Evaluating the 3D depth of the image could potentially be done using a stereoscopic camera rig. Performing mathematical analyses on the images captured would allow the depth information to be recovered. This data would allow quantification of the how '3D' the screen image appears, and offer some measurement of which properties of the system have the strongest positive effect on viewer stereopsis.

The use of a pair of cameras within the system could potentially allow the collection of depth information with respect to touch events or viewer proximity. This allows the system to detect an object's position relative to the screen, which could have applications in many different areas.

The simulation described in section V illustrated that the viewing windows of the system do not abut. In a true autostereo system, the perspective views should change instantly as the viewer moves their head, with no regions where multiple perspectives are visible. The system described has regions in between the viewing windows where the intensity is low and the eye can see both images. This is due to the fact that the exit apertures of the projectors are small in comparison to their separation. A method of addressing this could be to use a lenslet array to produce a 'top hat' type diffuser which only acts in the horizontal direction.

X. CONCLUSIONS

We have presented an autostereoscopic display capable of real-time interaction with the viewer. We have quantified the quality of the 3D image obtained, and minimized the relative distortion between views to approximately 0.4%. We utilized two small (115x50x22mm) pico-projectors as display devices which resulted in a screen contrast of 12.9, with the projector contrast being measured as approximately 30.8. Brightness was matched to an acceptable tolerance; less than 8%.

We have described how such a display can be expanded by use of a different Wedge variant, and given approximate dimensions of such a display. Important further work includes quantifying and correcting for Wedge distortions in real-time; examining the perceived image depth and constructing a larger system with more perspective views.

We have shown via the constructed display that the Wedge is capable of simultaneous display and imaging; it is a parallel waveguide display. This feature combined with its thin, large format means it could have many applications in numerous fields. The final display is shown in Fig. 16.

Fig. 16. A photograph showing the assembled system.

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