Prototyping a Light Field Display Involving Direct Observation of a Video Projector Array

Joel Jurik Andrew Jones Mark Bolas Paul Debevec
University of Southern California Institute for Creative Technologies
12015 Waterfront Drive, Playa Vista, CA 90045

Abstract

We present a concept for a full-parallax light field display achieved by having users look directly into an array of video projectors. Each projector acts as one angularly-varying pixel, so the display's spatial resolution depends on the number of video projectors and the angular resolution depends on the pixel resolution of any one video projector. We prototype a horizontal-parallax-only arrangement by mechanically moving a single pico-projector to an array of positions, and use long-exposure photography to simulate video of a horizontal array. With this setup, we determine the minimal projector density required to produce a continuous image, and describe practical ways to achieve such density and to realize the resulting system. We finally show that if today's pico-projectors become sufficiently inexpensive, immersive full-parallax displays with arbitrarily high spatial and angular resolution will become possible.

1. Introduction

Recent advances in display technology have enabled the proliferation of pixels across many display surfaces such as thin televisions, computers, and mobile devices. However, the vast majority of these experiences remain flat and two-dimensional. 2D displays only provide control over the spatial distribution of light, so the generated image remains the same when seen from different view points. To create a full-parallax autostereoscopic 3D display, it is necessary to also have precise spatial and angular control over light intensity so that different images can be seen from multiple viewing positions. This set of spatial and angular rays is commonly referred to as the *light field* generated by the display [6]. Many types of 3D displays have been contemplated and constructed in the last century, but only recent advances in digital capture, computation, and display have made functional and practical 3D displays possible. Nonetheless, for fundamental reasons described in [13], today's displays make unfortunate compromises in the trade-off between angular and spatial resolution.

One auspicious development is that video projectors are rapidly shrinking in size, power consumption, and cost. Such projectors will provide unprecedented flexibility to stack, arrange, and aim pixels. For example, new projectors based on the Texas Instruments PICO chipset use LED illumination and a DLP chip in a tiny $4.48cm \times 6.74cm \times 1.42cm$ body. As mobile companies announce plans to offer cellular phones incorporating miniature video projectors, we might expect that projectors may undergo further evolution in size, power, and cost following the vast gains made for cell phone cameras in recent years.

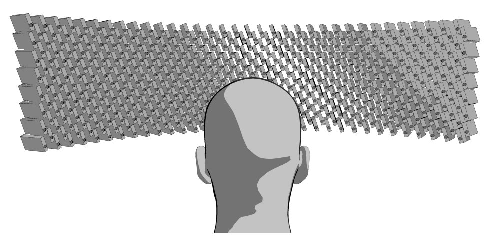


Figure 1. An illustration of a full-parallax light field display built from an array of miniature video projectors aimed directly at the viewer. With a sufficient number of projectors, arbitrarily high spatial and angular resolution can be achieved.

The possibility that pico-projectors may become very small and inexpensive suggests a new form of light field display: one where each and every "pixel" of the display is a video projector. An illustration of such a display is shown in Figure 1. The video projectors, all aimed toward and focussed upon the viewer, provide angularly varying pixels visible throughout the region where the projector beams overlap. As seen in Figure 2, the size of this region can be large enough to provide display for several people, and can be extended to provide full 360-degree immersion.

Since pico-projectors are not *yet* extremely inexpensive, we demonstrate the feasibility of this approach for the horizontal-parallax-only case using just one pico-projector. To do this, we mount the projector on a translation gantry which moves the projector to each of the positions in the

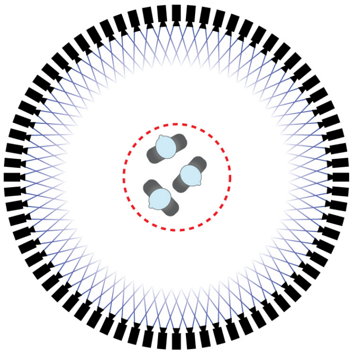


Figure 2. Surrounding viewers with a dense array of pico-projectors . Placing the projectors sufficiently far from the viewers (with correspondingly longer lenses) permits an arbitrary numbers of projectors to be used, achieving any desired scene resolution.

proposed multi-projector array. This setup allows us to test different spacings to determine the number of projectors needed to produce continuous imagery. We simulate the appearance of the full projector array by acquiring long-exposure photographs as the translating projector flashes views of the 3D scene toward the viewer. To show the effects of stereo and motion parallax, we translate the camera to acquire a horizontal sequence of such long-exposure photographs (see Figure 6). From these experiments, we show that a horizontal-parallax-only display with unprecedented angular resolution can be practically achieved using this technique, even with today's pico-projectors.

2. Previous Work

Many 3D display solutions employ parallax barriers or lenticular lenses mounted onto a high-resolution 2D display. This idea dates back to integral photography [7]. In this approach, the spatial resolution of the 2D display is decimated to provide a smaller number of angularly-varying pixels. Horizontal parallax only (HPO) displays using this approach are commercially available today, and full parallax displays using lenslet arrays have been proposed and demonstrated in systems such as [12] and [10]. [13] analyzes the performance of these displays, and shows that their limited angular resolution gives them extremely shallow depths of field. Commercial displays which interleave eight views angularly produce images which become blurry any further than 32mm from the display surface, and even on the display surface, the images are significantly lower-resolution than standard definition due to the spatial decimation. Even worse, the image views typically repeat so users can not move freely around the display and may not see the correct view corresponding to their relative position.

3D displays based on true 3D holography dynamically recreate the actual light waveform emanating from a 3D scene. While classic holograms capture static scenes on specialized photographic film, new systems have demonstrated the display of dynamically-updated scenes [1, 11]. Unfortunately, current systems have limited update rates as well as significant restrictions on image size, field of view, and color depth. As such, existing holographic technology is not suited for large-scale immersive environments. The search for novel optical materials for dynamic holography is an active area of research.

Building a 3D display from arrays of projectors is not in itself new. In 1931, H. Ives demonstrated that if the back of a vertically-oriented lenticular screen is painted diffuse then one could focus pixels from a large number of projectors to recreate different views [4]. While Ives originally used 39 slide projectors, more recently Matusik and Pfister's 3DTV [8] demonstrated a live autostereoscopic display using a similar screen design but with 16 video projectors. In both cases, light actually passes through the vertically-oriented lenticular screen twice. The first lenticular focuses the projector pixels onto the diffuse or retro-reflective backing, and the second redistributes the pixels to different angular directions. The combination of relatively wide projector spacing and horizontal diffusion in the screen made the angular resolution of the system relatively low; objects in front of or behind the display became blurry quickly, and the sense of motion parallax was weak. As resolution increases, it becomes harder to align the lenticular screens to avoid artifacts or unwanted reflections.

The commercial Holografika system [2] uses an array of video projectors projecting through a holographically diffusing screen. While many technical details are proprietary, the system claims an angular resolution of two degrees between views at any point on the screen [3]. This limited angular resolution requires significant horizontal diffusion to produce a continuous image from the projectors. The results is a relatively shallow depth of field and a weak sense of motion parallax. [9] constructed a prototype light field display using a 5x4 array of video projectors, but suggested that projecting through a lenslet array would be necessary to bring the device up to a practical resolution.

A mechanical element can also be used to display different images to multiple viewers. Jones et al. [5] project high-speed video onto a rapidly spinning mirror made from brushed aluminum. As the mirror turns, it reflects sequential projector frames to different potential viewers. If one were to unfold the optical path, their mirror system produces the effect of 288-projectors illuminating an anisotropic display surface viewable from 360 degrees around and with 1.25 degrees between views. While the display has the advantage of requiring only a single physical projector, the challenges of spinning the mirror limit the overall size of the display volume. While their display targets the reproduction of small objects, ours targets the display of environments requiring deep depth of field. For our prototyping purposes, we also use mechanics to simulate a video projector array using just a single video projector.

We investigate the use of video projector arrays which do not rely on a diffusing surface to make up for insufficient angular resolution. Even when an additional screen is introduced to restrict the display to horizontal-parallax only device, we do not introduce any horizontal diffusion. Instead light is projected directly onto the observer. In this way, our display's spatial resolution is achieved through the sheer number of video projectors (the glow of each projector lens forms one pixel for a 2D array and one vertical line in a 1D array) and its angular resolution is the image resolution of each projector, which as a result is extremely high relative to previous systems. This represents a reversal of spatial and angular roles from previous projector array based displays, and solves their endemic asymmetry in spatial and angular resolution described in [13]. The result is a display capable of showing high-resolution imagery with a deep depth of field, potentially able to convincingly produce the effect of looking through a window into another world.

3. Apparatus

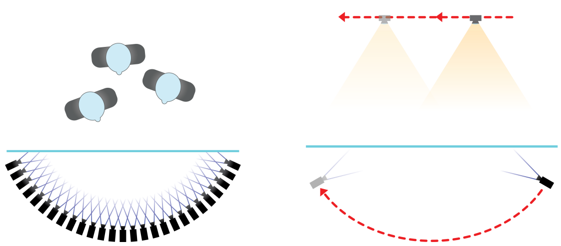


Figure 3. (Left) Top down view showing an array of pico-projectors behind a vertically diffusing screen, achieving a horizontal-parallax-only display. (Right) We simulate such an array by flashing different views of the scene along the arc from a single pico-projector. The camera records the summed effect of these flashes using long exposures.

The visual quality of a projector-based display is highly dependent on the number and spacing of projectors. Instead of constructing multiple instances of a full-projector array, we designed a motorized translation stage to discretely sample multiple pico-projector array designs with a single projector. While the projector moves through all possible positions, we capture a long-exposure photograph that records how the display would appear if all the projectors were illuminated at once. A 2D translation stage could be used to exhaustively move a projector through all horizontally and vertically positions but this would significantly increase the mechanical complexity and capture times. Instead we use a 1D translation stage and a vertical scattering screen placed 170cm in front of the projector to simulate a horizontal-parallax only display. Once we have determined the ideal spacing in the horizontal direction, this information could then be applied to the vertical spacing in a 2D array. We are currently using an off-the-shelf lenticular screen material with a 50 degree vertical scattering angle and 60 cylindrical lenses per inch. The lenticular screen is mounted in a horizontal configuration to distribute the pixels to multiple heights even with a 1D array of projectors. In our tests we compared two existing pico projectors: an Optoma's PK201 Pico Pocket Projector with 864x480 pixel resolution, and the smaller Texas Instruments Pico development kit with 480x320 pixel resolution. In order to simulate an array of pico projectors, the single pico projector is attached to an adjustable aluminum bar, while the other end of the bar is connected to a pivot point directly below the vertical diffuser. This frame is then placed on an Arrick Robotics X Linear Positioner which translates 66cm. By translating the linear positioner, we can precisely position the projector along an arc of 27 degrees while aimed at the screen. As we iterate through the desired set of discrete projector positions, we display a corresponding sequence of rendered views of the scene. Each projector frame is visible for 60 milliseconds. Once the pico projector has moved the full length of the arc, the camera's shutter is closed and an image is recorded. The camera itself is mounted on a secondary translation stage. By repeating the same projector motion for different camera positions, we can analyze the generated motion parallax.

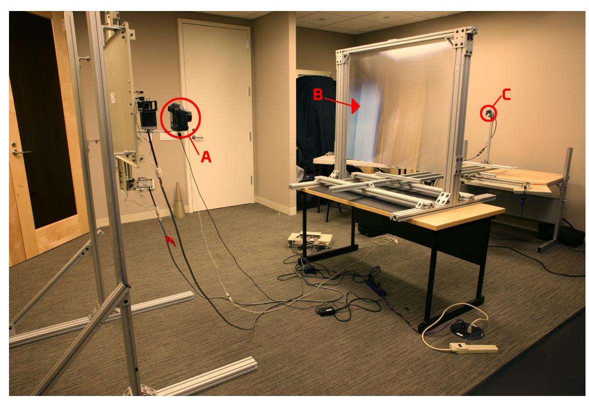


Figure 4. Proof-of-concept apparatus using (A) a long-exposure camera (B) a 42”x35” lenticular screen, and (C) a single pico projector on a mechanical translation stage.

4. Results

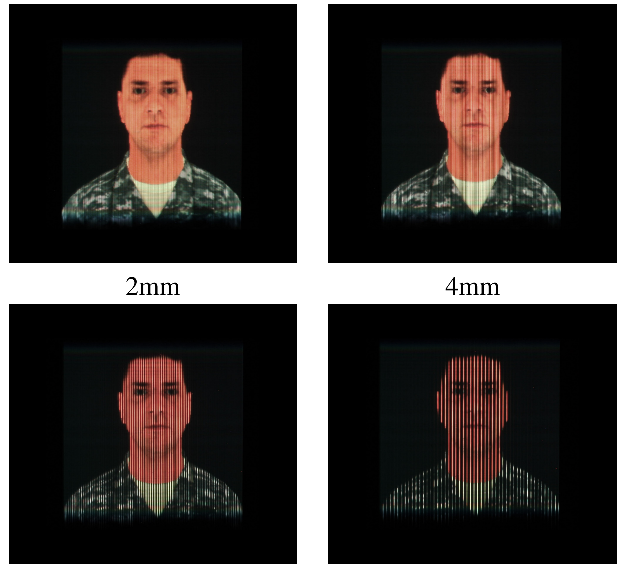
Our first experiment was to analyze how many projector positions are needed to create a seamless 3D image on the screen. As a baseline, we first recorded a sequence where the projector frames were shown continuously using the higher-resolution Optoma PK201. This result is available in the supplemental video. We then discretely sampled the projector arc at multiple densities including 2mm, 4mm, 8mm, and 16mm between projectors using the smaller TI

Pico projector. Our test scene was a static 3D human model centered at the depth of the vertical diffuser. As seen in Figure 5, the 16mm and 8mm spacings exhibit noticeable gaps as the projectors are too far apart. In comparison the 4mm and 2mm spacings approximate a continuous image, owing to the fact that the exit pupil of the projected image is approximately 4mm in diameter. The video does show noticeable brightness variation from frame to frame and between adjacent vertical lines, which we believe is due to vibrations of the linear translation stage which would not occur for a full array of projectors.

Our second experiment tested the display's effective depth of field. Autostereoscopic displays with insufficient angular resolution typically exhibit blurring as objects move away from the screen. Given a 4mm spacing between projectors and a viewer distance of 320cm from the array (and 150 cm from the vertical diffusing screen) the test bed has an approximate angular resolution of 7.4 distinct views per degree and an average 1.58mm pixel separation on the screen. An observer would be provided 20 distinct images between the eyes at a distance of one meter from the screen. [13] provide a formula for depth of field that can be adapted to this projector array. In the 4mm case, the apparent depth of field is $\pm$67cm - the distance an object must be from the screen before there is a noticeable drop in resolution. In contrast, a typical commercially-available LCD lenticular autostereoscopic display has a depth of field of less than $\pm$3.2cm [13]. This large depth of field makes a dense pico projector array much more suitable for displaying large-scale environments. In Figure 6, we place an additional teapot and a wall 20 cm in front and 120cm behind the human model. Despite significant depth, both the wall and the teapot remain sharp and show smooth motion parallax.

5. Building a practical display

To physically construct a 3D display with 4mm projector spacing requires practical solutions for mounting and controlling such a large number of projectors. While the TI Pico projector has a thickness of 14mm, the projectors can be arranged in multiple rows (a technique also employed in [8]) to achieve narrower spacing. Figure 7 uses eight pico-projectors to demonstrate such an arrangement with four rows, achieving just under a 4mm offset between the rows. The top and bottom projector rows are reflected in mirrors to minimize the total vertical disparity, and the remaining vertical offsets should not be noticeable given the large vertical diffusion of the screen material. For many applications, a horizontal-parallax only display is acceptable since viewpoints tend to move horizontally rather than vertically, and such displays can be made to simulate vertical parallax by tracking the viewers as in [5] to dynamically update the vertical perspective for each viewer.



2mm 4mm

8mm 16mm

Figure 5. Long-exposure photographs of the display prototype with different spacings between projector positions. Wider spacing results in visible gaps between pixel columns.

Our current prototype with 4mm spacing provides 200 proxy projector positions over 80 cm. Feeding imagery to all 200 480x320 pixel projectors requires 30.7 megapixels to be rendered. This is a significant number, but is well within the capabilities of current graphics hardware. The ATI FirePro series of graphics cards produce six Displayport video signals with resolutions up to 2560x1600 pixels, yielding 24.6 megapixels per card. Also, up to four cards can be hosted in one computer. By rendering tiled images to the graphics cards, and using custom video processing modules to divide the high-resolution video signals into multiple pico-projector video signals, generating the 200 video signals could be accomplished even on one computer.

Notably, while this display provides only 200 pixels of spatial resolution from the 200 projector positions, it produces a relatively symmetric 320 samples of angular resolution (and this would increase for higher-resolution pico-projectors). This is notable since at this resolution the imagery observed by the viewer can change completely if they move as little as 4mm left or right in the convergence area of the projector beams. Since this distance is as small as the diameter of a contracted pupil, the display should provide realistic motion parallax (in addition to binocular stereo), and is approaching the resolution required to provide cues of visual accommodation (in the horizontal dimension). In the video, we see that the display simulated using long-exposure photography shows sharp imagery and smooth motion parallax for background, middle-ground, and foreground objects.

We can also consider the requirements for extending this design to a full-parallax display as in Figure 1. In concept,

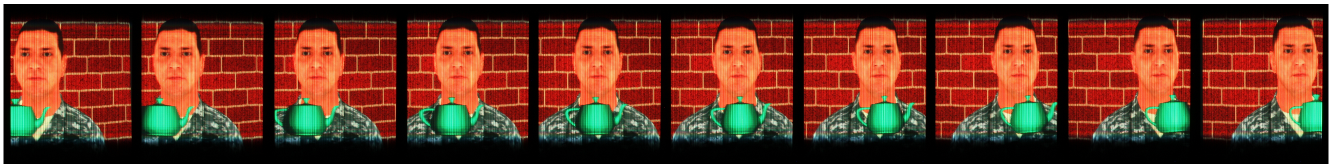


Figure 6. Long-exposure photographs of the display prototype from different camera positions with 4mm spacing between projector positions. Neighboring images can be seen in 3D through cross-fusion. Horizontal parallax is visible between teapot, human, and wall at different depths; the deep depth of field allows all three objects to remain in focus with smooth motion parallax (see accompanying video).

one could stack several horizontal-parallax 1D arrays on top of each other, but in the previous design we already used the vertical dimension to stagger the projectors for tighter spacing. However, since the the projectors are arranged in a circle, we can simply increase the radius of the circle until the projectors have enough room to be placed side-to-side with enough space between them to allow additional rows to be placed above and below isotropically; Figure 1 shows an example of such an arrangement. As the radius of the display increases, longer focal length optics on the pico-projectors must be adjusted to keep them focussed over the same working display area. Note that at such distances, the lenses of the pico-projectors may cover only a small amount of the total viewable field, appearing as small points of light in a dark field. This is not necessarily a problem, since 2D LED display walls typically produce just such a visual field in order to increase the display's contrast ratio in the presence of ambient light. When viewed from sufficiently far away, the points of light visually connect to form a continuous image.

From simple multiplication, generating standard-definition 640x480 video signal with full 3D parallax in this manner would require three hundred thousand pico-projectors, and an HD 1920x1080 video signal would require two million pico-projectors. With such numbers, one must hope that pico-projectors will become a commodity item costing under one dollar each. This is certainly possible in the coming decades: miniature camera units with lenses and imaging arrays for cell phones can be purchased this inexpensively already, as can LED light sources, and both used to be relatively expensive. At this point, only the computational power needed to generate the imagery for the displays will be in doubt. We note however that it will only be necessary to generate the imagery near the position of each viewer's eyes, and that rudimentary viewer tracking would be able to narrow down a safe set of pixels to compute. The rest of the light field could be ignored, or rendered and displayed at very low resolution to illuminate the viewer's bodies with lighting consistent with the scene they are observing (otherwise, only an area near each viewer's eyes would receive light, which could appear strangely to other participants).

We can finally consider what would be necessary to produce an image which might approach the realism of looking through a window into the real world. Human visual acuity is frequently cited as approximately 0.6 arc minutes per line pair. Assuming two pixels of width are needed to display a line pair, this would require 72,000 projectors to encircle the viewers for a horizontal parallax display. At 4mm projector spacing, this would be nearly a 100m-diameter circle. However, we note that recent "Retina" displays on cell phones are 128 pixels/cm and are designed to be seen from a distance of approximately 30 cm, implying that only 24,000 projectors might be necessary for very convincing imagery. If eight rows of projectors could be staggered to allow 2mm projector spacing, then such a display could be realized in a 15m display diameter, providing smooth motion parallax over a volume exceeding a diameter of one meter. Such a form factor could be appropriate for a highly realistic driving simulator, for example, or to give two or three people a sense of being transported to other environments. But it remains to be experienced whether such an ultra-high-resolution horizontal parallax system will be fully convincing, as the the lag from vertical parallax tracking and lack of visual accommodation cues in the vertical dimension may still degrade the illusion. It is possible that completely convincing telepresence may require full-parallax displays, which could require more than a decade or two to achieve using millions of projectors.

We finally note that these types of displays should have little difficulty achieving high brightness levels, as looking directly into video projector lenses yields notably bright imagery (even after vertical diffusion). This bodes well for the miniaturization of the projector elements, since the light output requirements for each projector-pixel are quite modest.

6. Future Work

The first item of future work will be to construct a complete horizontal-parallax-only version of the display using the 4mm pico-projector spacing and approximately 200 projectors. Having the imagery be produced by many different projectors will require designing a calibration procedure to achieve alignment and brightness consistency. We will also need to develop a vertex shader to render perspective-correct imagery to the display for any viewer height, following the multiple-center-projection technique in [5]; currently, we approximate the projection with an orthographic mapping. Adding a viewer tracking system such as a Mi-

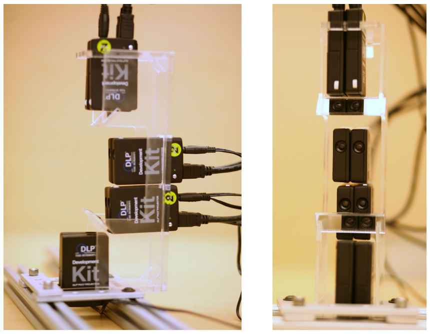


Figure 7. A prototype mounting arrangement which places 14mm-wide pico-projectors every 3.5mm horizontally. The two 45 degree mirrors allow for closer vertical packing, and vertical diffusion allows the projectors to be placed at somewhat different heights. The prototype shows 8 projectors in an arrangement which could be extended to a horizontal array with hundreds of projectors.

crosoft Kinect would allow for tracked vertical parallax to be offered to multiple viewers. For a full-parallax display, standard perspective projection can be used corresponding to projection matrix of each projector, with the clipping planes reversed so that the viewer sees the surfaces furthest from the centers of projection instead of closest. We envisage that a small array of graphics cards should have the power to render rich dynamic content for such a large projector array.

7. Conclusion

In this work, we have shown simulations which suggest that practical arrays of pico projectors can produce autostereoscopic 3D displays with notably high angular resolution. Our display concept achieves its high angular resolution by avoiding the need for horizontal diffusion through its sheer number of video projectors. Based on these findings, the path is clear to physically realize a horizontal parallax 1D array with currently available hardware. As the cost of small projectors decreases, we have shown that it will become practical to construct 360-degree immersive environments with both high spatial and angular resolution. If the cost becomes very low, 2D arrays of pico projectors using no screen whatsoever may provide for extremely compelling light field displays, perhaps just as realistic as looking out a window or experiencing the fictional Holodeck of Star Trek. Today, the Fremont Street Experience in Las Vegas sports an enormous 2D display comprising 12 million color LEDs. In the decades to come, millions of tiny video projectors may provide an immersive 3D experience indistinguishable from reality.

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