LCD Masks for Spatial Augmented Reality

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ABSTRACT

One aim of Spatial Augmented Reality is to visually integrate synthetic objects into real-world spaces amongst physical objects, viewable by many observers without 3D glasses, head-mounted displays or mobile screens. In common implementations, using beam-combiners, scrim projection, or transparent self-emissive displays, the synthetic object's and real-world scene's light combine additively. As a result, synthetic objects appear low-contrast and semitransparent against well-lit backgrounds, and do not cast shadows. These limitations prevent synthetic objects from appearing solid and visually integrated into the real-world space. We use a transparent LCD panel as a programmable dynamic mask. The LCD panel displaying the synthetic object's silhouette mask is colocated with the object's color image, both staying aligned for all points-of-view. The mask blocks the background providing occlusion, presents a black level for high-contrast images, blocks scene illumination thus casting true shadows, and prevents blow-by in projection scrim arrangements. We have several implementations of SAR with LCD masks: 1) beam-combiner with an LCD mask, 2) scrim projection with an LCD mask, and 3) transparent OLED display with an LCD mask. Large format (80" diagonal) and dual layer volumetric variations are also implemented.

Keywords: LCD Masks, Transparent LCD, Spatial Augmented Reality, Beam-combiner, Scrim, Transparent OLED

1. INTRODUCTION

In the entertainment, advertising and information visualization fields, there is often a desire to place synthetic imagery (e.g. objects or information) into real world scenery casually observable by many viewers. Using 2D screens, the synthetic object appears on the screen surface or at best behind the screen in a synthetic world. Although 3D stereoscopic images can appear to "pop out" of the screen, the synthetic object's apparent location will change with viewer movement due to the fixed disparity of the two views. Even augmented reality mobile applications suffer from the screen surface being the primary locus of interaction. The display screen is a window into a synthetic world, and the synthetic object is not integrated into the real world. One aim of Spatial Augmented Reality (SAR)[1] is to visually integrate synthetic objects into real-world spaces amongst physical objects, viewable by many observers without encumbrances of 3D glasses, head-mounted goggles or mobile screens. Common implementations uses beam combiners, scrim projection, or near-future, transparent self-emissive displays.

An optical combination of synthetic imagery and real world scenery can be achieved using a beam-combiner – a partially-silvered mirror sometimes referred to as a beamsplitter. The reflected image of a display or object in a 45° angled beam-combiner is optically overlaid onto a real scene behind the beam-combiner. Variations of this method are used in Pepper's Ghost illusions, heads-up-displays (HUDS), and see-through head-mounted-displays (HMDs). This technique has its limitations. HUDs are typically semi-transparent two dimensional overlays for a single observer (e.g. driver or pilot). Optical-see-through HMDs are limited to the single observer wearing goggles, often monocular and require head-tracking. The Pepper's Ghost illusion is the most general as it presents dimensional synthetic images to a large number of casual observers. However in recent incarnations, the illusion has traded off the dimensionality of physical objects for the programmable flat imagery of a 2D display.

Scrim projection is another common technique used in theatre for placing synthetic objects into real world sets. Scrim is an open weave material that scatters light off its threads but also allows light to pass through the openings. Combined with lighting techniques, it is often used for a variety of special effects, such as reveals or environmental effects. Scrim may also be used as a projection surface. When the scene behind the scrim is well lit but the scrim is not, the scrim is transparent. Projecting onto the scrim, the image scatters off the scrim becoming visible, but the remainder of the scrim is still transparent. The background scenery is still visible through the scrim, making the projected image appear in the middle of the set but also semitransparent and low contrast. Furthermore, the projected imagery also passes through the scrim's opening and may appear on the set and set pieces.

More recently, it is a fashionable technique to place a layer of information or advertising on a transparent display in front of merchandise. Typically these displays use transparent liquid crystal displays (LCD) in the front panel of a very bright light box containing the merchandise. The light box is required because the liquid crystal panel does not generate its own light; rather the liquid crystal varies the amount of light that passes through a set of crossed polarizers. Against dark

Stereoscopic Displays and Applications XXV, edited by Andrew J. Woods, Nicolas S. Holliman, Gregg E. Favalora,
Proc. of SPIE-IS&T Electronic Imaging, SPIE Vol. 9011, 90110O · © 2014 SPIE-IS&T
CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2035091

backgrounds or objects, the synthetic object cannot be seen; and against bright backgrounds the synthetic object appears semitransparent. In the near future, transparent self-emissive displays (e.g. transparent OLEDs) are a possible substitute for the transparent liquid crystal display and light box.

However in each of these cases, the synthetic object's and real-world scene's light combine additively. Therefore, synthetic objects appear low-contrast and semitransparent against well-lit backgrounds, and they do not cast shadows. These limitations prevent synthetic objects from appearing solid and visually integrated into the real-world space. Also, most techniques do not support multiple user 3D imagery. We propose using dynamic masks to help integrate programmable high contrast, opaque synthetic dimensional objects into physical space including mutual occlusion and shadows, simultaneously viewable by many casual observers.

2. RELATED WORKS

2.1 Beam-Combiners

Research and continuing advances are addressing the limitations of beam-combining in HUDS, HMDs, and even Pepper's Ghosts. In theatre and similar entertainment applications which use the Pepper's Ghost illusion (or scrim projection), the background behind the synthetic character is made as plain and/or dark as possible, and the synthetic character itself is textured using light colors, including using the "day for night" effect with bright but desaturated blue tinged lighting and shadows. The effect depends upon light priority of the foreground synthetic character to overpower the background set's light and appear opaque. This limits the set design and creative intent.

Similarly, to increase the contrast of simple monochrome displayed symbols against the background, HUDs use extremely bright displays (e.g. laser scanned projectors) with wavelength selective beam-combiners. For use with synthetic objects, this method creates difficulties with consistent lighting of the object and real world scenery. The display's usable dynamic range is reduced to compensate for background lighting.

Research into simulating occlusion and shadows has been conducted using viewpoint masks and programmable lighting. Kiyoshi [1] and Tatham [2] handle occlusion using near-eye LCD masks and rendered shadows for a single viewpoint in HMDs, but as mentioned, an HMD is for a single viewer wearing head-tracked goggles. A synthetic model of the scene must exist and the viewpoint must be tracked to compute appropriate occlusion and shadows. To view 3D images, two monocular HMDs must be worn.

Bimber simulated occlusion and shadows in Pepper's Ghost arrangements using programmable projection lighting [3]. For a single viewpoint, the portions of the background and background objects that would be occluded by the synthetic object are not illuminated by a projector providing scene illumination. Ambient and diffuse light may spoil the effect by leaking into these synthetically occluded background areas. The effect works for a single viewpoint and requires head-tracking.

To simulate shadows, the ground surface and objects that would receive cast shadows from a synthetic object are not illuminated by the projector. Dynamic objects that move between the projector and the synthetic object may be incorrectly lit. In both the occlusion and simulated shadow case, a synthetic model of the scene must exist and the position of all objects must be known to compute the appropriate projected illumination.

Bimber also addressed means to allow multiple users to view dimensional synthetic and real objects in shared space [4]. The "Synthetic Showcase" provides for multiple users by using an inverted pyramid of four beamsplitters each reflecting a different perspective of a synthetic object tiled on a single display. Each viewer is assigned a separate pane. Each perspective is a single 2D view, so the object would appear planar and would not have continuous motion parallax. Headtracked 3D glasses enable each viewer to see a three dimensional object encased in the pyramid with continuous motion parallax, but multiple viewers are not able to share the same pane. Synthetic objects appear to share space with real objects, but the shared space is enclosed in the pyramid, and the synthetic object appears semi-transparent.

All these techniques fall short of our goal of visually integrating a synthetic dynamic character into a real world scene for viewing by multiple casual observers. The dynamic synthetic character must be high contrast and appear solid, capable of occluding background objects and being occluded by foreground objects (mutual occlusion), be able to cast shadows, be viewable from a large number of viewpoints, and be dimensional without the encumbrances of 3D glasses, goggles or mobile screens.

3. METHOD

The three common implementations of SAR each use an intervening medium to scatter, redirect or generate light to make it appear as if the light came from the synthetic object located within the set. However, to occlude the background, to exhibit dark textures, and to cast shadows, we also need means to block and absorb light as well. Therefore, we need a display system that is capable of emission, absorption, and transparency; typical displays only achieve two out of three.

To achieve an additional absorbing state, we combine the transparent/emissive display with a transparent/absorbing display. In this work we use a transparent LCD panel, which as previously explained, modulates the amount of light that passes through it. The LCD panel is located at the plane of the synthetic object in the physical world and displays the synthetic object's silhouette, acting as programmable dynamic mask. The mask blocks the background providing occlusion, presents a black level for high-contrast images, blocks scene illumination thus casting true shadows, and prevents blow-by in projection scrim arrangements. The mask is colocated with the object's color image, both staying aligned for all points-of-view.

We have several implementations of SAR with LCD masks: 1) beam-combiner with an LCD mask, 2) scrim projection with an LCD mask, and 3) a transparent OLED with an LCD mask including large mask and dual layer variations.

3.1 Beam-Combiner with LCD Masks

In the first configuration, we combine a traditional Pepper's Ghost illusion with an LCD mask. A traditional Pepper's Ghost is accomplished with a beam-combiner and a display. The beam-combiner is placed at 45° to the display's surface. The distance between the display and the beam-combiner determines the location of the semi-transparent synthetic image in the physical set. The space between the beam-combiner and display is the dual of the space between the beam-combiner and the object. Unfortunately, the reflected object created in this setup only appears solid and high contrast against a background that is as empty and dark as possible.

We extend the use of beam-combiners by using a dynamic mask in the shape of the object's silhouette placed at the reflected virtual image plane of the traditional illusion. It is convenient to think of the dynamic mask as a moving, programmable stencil that holds-out a place for the synthetic image. The resulting dark empty space allows for a high contrast reflected image. The mask also occludes background objects creating the appearance of solidity. Furthermore, the mask also blocks scene lighting and therefore casts true shadows. This adds a sense of presence to synthetic objects. The result is an opaque, high contrast, but ultimately flat synthetic character embedded in the physical set.

While the mask occludes the background, the color image of the synthetic character will still be combined with foreground objects between the mask and the beam-combiner. Additional masks are added to allow physical objects in the foreground to occlude the synthetic character. A "phantom" mask or object (a black version of the foreground object) is placed in front of the reflected display (in the dual set) at the virtual image of the foreground physical object. From different viewpoints, the phantom object will stay aligned with the occluding physical object, and correct motion parallax and occlusion with respect to the synthetic character occurs naturally.

3.2 Beam-Combiner with Multilayer Display and LCD Masks

To overcome issues of flat imagery, instead of using a single reflected 2D display, we may use an autostereoscopic dimensional display. We employ a volumetric multilayer display for its particularly simple and effective means of producing multiple depth cues and its relative ease of incorporation into the beam-combiner with LCD mask display. Indeed, the multilayer display is implemented using an additional beam-combiner to optically layer two displays separated by the thickness of the synthetic character. Then, using depth antialiasing [2] as in the DepthCube display (a twenty plane volumetric display)[2] and the Depth Fused Display (a dual layer display) [5] we can place a virtual pixel at any depth between the two displays. The character appears smoothly dimensional. This three dimensional image is optically superimposed on the dynamic mask to give the illusion of volume and solidity.

The use of a multilayer display that only spans the thickness of the character and is visually colocated with the character's position in the set is advantageous, especially with the volumetric appearance achieved with depth antialiasing. If the spacing of the two displays are within the eye's depth of field, likely with a single character in a set, depth antialiasing suppresses inconsistencies in accommodation and vergence and the eyes will naturally focus at the virtual pixel rather than at the display surfaces [6]. The virtual pixels at different depths also exhibit consistent continuous motion parallax within the viewing zone [6]. The character will appear natural without eyestrain.

For certain locations of an occluding foreground object, its phantom mask or object is located within the multilayer display. In these cases, two phantom objects are needed: one for the front layer display, and another for the back layer display, placed such that both their reflections overlay each other and the occluding foreground object.

3.3 Scrim Projection with LCD Masks

Projection onto scrim is another common means in theatre for adding synthetic objects into real world sets. The scrim's open weave material scatters the projected image but also allows the background to be seen. Scrim projection does not require the large mirror and dual set arrangement of the Pepper's Ghost, so it is more compact. Phantom objects are not needed to provide occlusion by foreground objects.

Because the scrim material is very fine and open, the background and projection appear combined. Like the Pepper's Ghost illusion, the projected synthetic objects still appear semitransparent and low-contrast unless against a dark plain background. Scrim projection also has issues with "blow-by" wherein the projected image also passes through the scrim and appears on background objects. This is usually ameliorated by using steep projection angles so the blow-by is limited to a small area of the set which can be hidden or blocked, and "no-go" areas on the scrim where projection is not allowed thus preventing blow-by onto the background.

To address scrim projection's issues for our intended purposes while preserving its beneficial properties, we again use a programmable mask. Here a transparent LCD panel is placed behind and in contact with the scrim, displaying a matching black silhouette mask corresponding to the projected image. The mask blocks the background so the synthetic object appears opaque and provides a black level to produce high contrast imagery. The mask also blocks the projected image that passes through the scrim from continuing onto the background, thus preventing blow-by.

3.4 Transparent OLED displays with LCD Masks

Both the Pepper's Ghost and scrim projection implementations require image sources separate from the location of the synthetic object. Ideally, the image source would be colocated with the synthetic object. Transparent OLED displays would initially appear to be an ideal candidate since they are transparent and self-emissive. Unfortunately, they cannot controllably absorb light and thus cannot provide black nor dark colors against bright backgrounds, nor block light from the background nor a luminaire. Therefore, similar to the Pepper's Ghost and scrim projection, a transparent OLED display's images will also be semitransparent and low contrast.

Following our current approach, we can stack a transparent LCD panel behind the transparent OLED display to provide a black level and block background light. Currently, transparent OLED displays mainly exist as research prototypes (e.g. Samsung 14" transparent OLED display at CES 2010) except for a small commercial 2" low-resolution (160x120 pixels) transparent OLED display module by 4D Systems. Although small, the combination of the 2" transparent OLED display and a small LCD module will demonstrate the capability and improvements made by combining the two modules.

4. IMPLEMENTATION

4.1 Beam-Combiner with LCD Masks

A 27" Asus VG278 monitor with its backlight and antiglare diffusing film removed becomes a transparent LCD panel, a second 27" television displays the synthetic color object, and a glass plate acts as a beam-combiner. The glass plate is placed at a 45° angle above the color display, reflecting its image combined with the background imagery towards the viewers. This forms a Pepper's Ghost of the display. The LCD panel is placed at the virtual image of the reflected display in the physical set, and displays the dynamic mask. (Fig.1).

Physical scenery and props are placed into the scene: a backdrop of a sky and farm, a physical tree in the background set, a split bush that straddles the LCD mask panel where the synthetic alien and cow will appear. Lighting comes from spotlight behind and to the upper left of the scene, as well as from ambient room light. LCDs attenuate light, so lighting behind the panel is controlled with a variable autotransformer to ensure equal illumination in front of and behind the LCD panel. The synthetic objects are rendered with virtual lighting in the same relative location and direction as the lighting in the physical set, so the synthetic objects appear consistently lit with the rest of the scene.

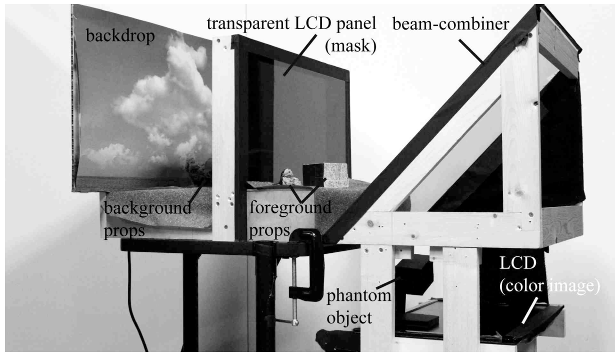

Figure 1. Setup of a beam-combiner with an LCD mask.

Using Quartz Composer (Apple Inc.) running on a Mac Pro tower, corresponding color and mask images from an animated sequence are displayed on a single large window spanning two displays using a Dual-Head-2-Go (Matrox) multi-display adapter. Display calibration is performed by displaying a grid image and grid mask on the two displays, then translating, rotating, and scaling the grid image until the image and mask are aligned. An animated sequence is displayed, consisting of a 10 second clip showing an alien space ship descending above a cow grazing in a pasture, then engaging a tractor beam to levitate and abduct the cow. For each frame of animation, color and mask images are prerendered from animated 3D models [7] using Wings 3D (Izware) and Strata 3D CX (Corastar).

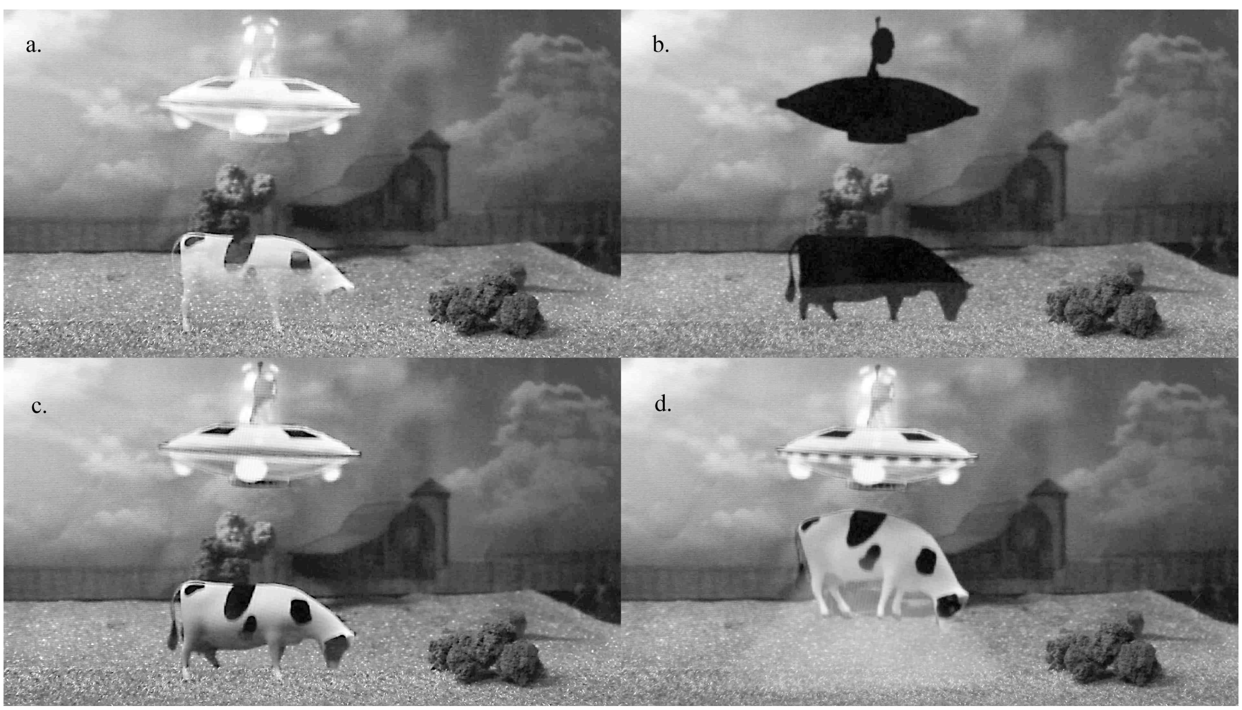

Figure 2a,b,c,d Images from a beam-combiner with LCD mask.
a.Traditional Pepper's Ghost, b. LCD mask image,
c. Pepper's Ghost with an LCD mask, d. Another frame exhibiting opacity and transparency

Figure 2a shows a traditional Pepper's Ghost reflection of a single monitor displaying one frame of an animated synthetic cow overlaid onto the physical set. The synthetic cow is low contrast and semitransparent with the backdrop and background trees apparent.

Figure 2b shows just the masks displayed in the transparent LCD panel.

Figure 2c shows a Pepper's Ghost with an LCD mask. The reflection of a single monitor is colocated with a dynamic LCD mask and overlaid onto the physical set. The synthetic cow is now high contrast, opaque and occludes the background trees and plate. The scene is inherently wide angle viewable.

Figure 2d shows another image of a Pepper's Ghost with an LCD mask. The synthetic cow is opaque, but the synthetic cockpit dome and tractor beam are semitransparent because they have no corresponding LCD mask.

A foreground textured cube prop – a bale of hay – is added in front of the synthetic character. A phantom object (a black painted cube) is placed near the display panel to mask the color image, allowing the foreground bale to occlude the synthetic cow. Back sides of props facing the modified LCD panel are painted black to prevent their reflected images from appearing in the panel.

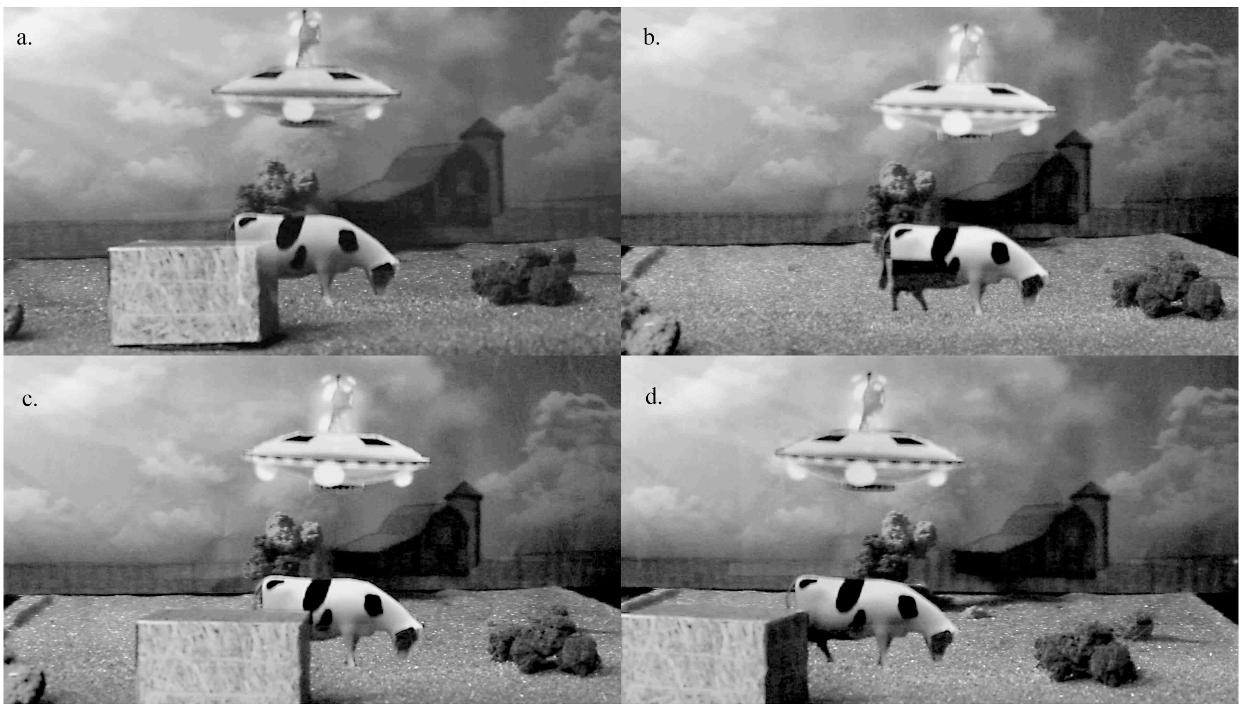

Figure 3a,b,c,d. Images from a beam-combiner with LCD mask, foreground object and phantom masks.
a. Pepper's Ghost with LCD mask and a foreground object, b. Foreground object removed with phantom object present,
c.Foreground object w/phantom object, d. Another view of beam-combiner with LCD mask, foreground object and phantom masks

Figure 3a shows an image of the Pepper's Ghost with an LCD mask and the foreground object. The foreground object is located between the beam-combiner and the LCD mask. Note that the synthetic cow is visible through the foreground cube.

Figure 3b adds a phantom object between the beam-combiner and the display (in the dual set space) at the reflected image of the foreground cube; the foreground cube is removed. In the reflected color image, the synthetic cow's color image has been partially blocked and the mask behind it is visible.

Figure 3c returns the foreground object between the beam-combiner and the LCD mask. The foreground bale now appears to occlude the synthetic cow.

Figure 3d shows a different viewpoint, exhibiting proper 3D occlusion and parallax between the synthetic object and the physical foreground and background.

4.2 Beam-Combiner with Multilayer Display and LCD Masks

The previous beam-combiner with LCD mask is modified by replacing the reflected display with a multilayer display (see figure 4). Two matched 25” displays are placed at right angles to each other; one placed vertically and one placed flat horizontally. A beam-combiner is formed using a glass plate with a 50/50 reflective coating placed at a 45° angle between the two displays. The displays are spaced such that the reflected image of one is slightly displaced in front of the other display. This forms the multilayer display. The multilayer display is reflected into the physical set using another beam-combiner formed by a glass plate with a 50/50 reflective coating placed at a 45° angle above the two displays. This forms a Pepper’s Ghost of the multilayer display.

A 25” transparent LCD panel acts as the programmable dynamic mask. An LCD panel from a commodity monitor is modified to increase its transparency. The LCD panel is separated from its backlight and has the antiglare film removed. The LCD panel is placed at the image of the reflected multilayer display in the physical set, specifically at the reflected image of the rear display.

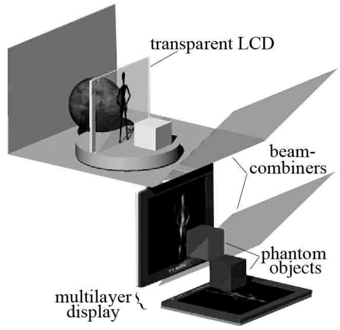

Figure 4. Setup of beam-combiner with multilayer display and LCD masks.

Physical scenery and props are placed into the scene: a background monitor displaying a logo, a physical globe background object, a split raised stage that straddles the LCD mask panel where the synthetic “jumping mannequin” will appear, and a foreground cube on the stage in front of the synthetic character. A half-wave plate polarizer sheet is placed on the background LCD display to prevent its image from being extinguished by the transparent LCD’s initial polarizer. Two phantom objects (black painted cubes) are placed near the two panels of the multilayer display to act as masks, allowing the foreground cube to occlude the synthetic mannequin. The back side of the foreground prop facing the modified LCD panel is painted black to prevent its glare image from appearing in the panel.

Lighting comes from a spotlight behind and to the upper right of the scene, as well as from ambient room light. LCD panels attenuate light, so lighting behind the panel must be controlled to ensure equal illumination in front of and behind the LCD panel. The synthetic character is rendered with virtual lighting in the same relative location as the lighting in the physical set, so it will appear consistently lit with the rest of the scene.

A repeating animated sequence is created consisting of mannequin performing jumping jacks. For each frame of animation, color, depth map and mask images are rendered for computing the depth antialiasing. The front panel composite is created as follows: the color image is converted to an Lab* color space, the intensity (L) multiplied by the corresponding depth map, and the resulting image converted back to RGB color space. Images for the rear panel composite are similarly created except the intensity (L) of the color image was multiplied by the complement of the corresponding depth map. Using Quartz Composer running on a Mac Pro tower, sequential frames of front and rear images and the mask were displayed on a single large window spanning three displays using a Matrox Triple-Head-2-Go adapter.

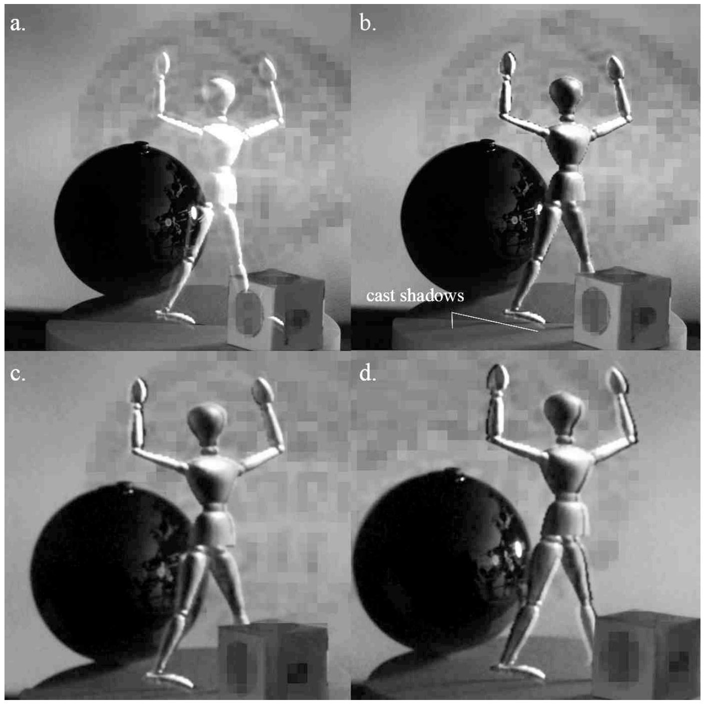

Figure 5a,b,c,d Images of beam-combiner with multilayer display and LCD masks.
a. Traditional Pepper's Ghost, b. Pepper's Ghost with multilayer display, LCD mask and phantom object,
c. Off-axis view, d. Far off-axis view [Backdrop and prop textures intentionally mosaiced].

Figure 5a shows a traditional Pepper's Ghost of the reflection of a single monitor displaying one frame of an animated synthetic mannequin overlaid onto the physical set. The synthetic mannequin is flat, low contrast, semi-transparent with the background plate and background globe apparent, and can be seen through the foreground cube object.

Figure 5b replaces the single display with a multilayered display and adds the LCD and phantom masks. The synthetic mannequin appears rounded and dimensional and is occluded by the foreground cube. True animated shadows are cast by the mask onto the stage.

Figure 5c shows an off-axis view of the setup in Figure 5a. The character is still dimensional but appears fuzzy as the front and rear planes (and mask) no longer match exactly. The mask also starts to become apparent as a dark outline.

Figure 5d shows an extreme off-axis view of the setup in Figure 5a. The front and rear planes no longer match at all, so the illusion of dimensionality and a coherent character is lost.

4.3 Scrim Projection with LCD Mask

A modified 27" Asus VG278 monitor, acting as a transparent LCD mask, is covered by scrim material (RoseBrand), and projected onto using an NEC LCD projector (Fig.6). The projection is significantly off-axis. To remove the keystoning in the projected imagery, a homography/corner pushpin calculation is used to perspectively warp and correct the projection. Using Quartz Composer running on a Mac Pro tower, sequential frames of color and mask images were displayed on a single large window spanning the display and projector using a Matrox Dual-Head-2-Go adapter. To calibrate/align the projection, a grid is displayed on the transparent LCD and a projected grid is warped until the two grids are aligned; the grid images are then replaced with the synthetic objects' masks and color images.

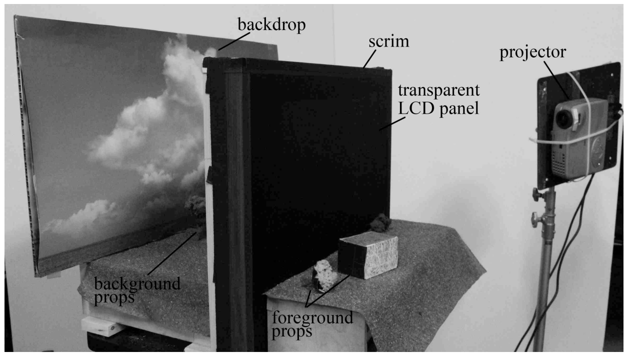

Figure 6. Setup of scrim projection with LCD mask.

Physical backdrop, scenery and props are placed into the scene: a backdrop of a sky and farm (~13" behind LCD panel), a physical tree in the background set, a split bush that straddles the LCD mask panel where the synthetic alien and cow will appear, and a foreground prop cube – a bale of hay – on the stage in front of the synthetic character. Lighting comes from spotlight behind and to the upper right of the scene, as well as from ambient room light. LCD panels attenuate light, so lighting behind the panel is controlled to ensure equal illumination in front of and behind the LCD panel.

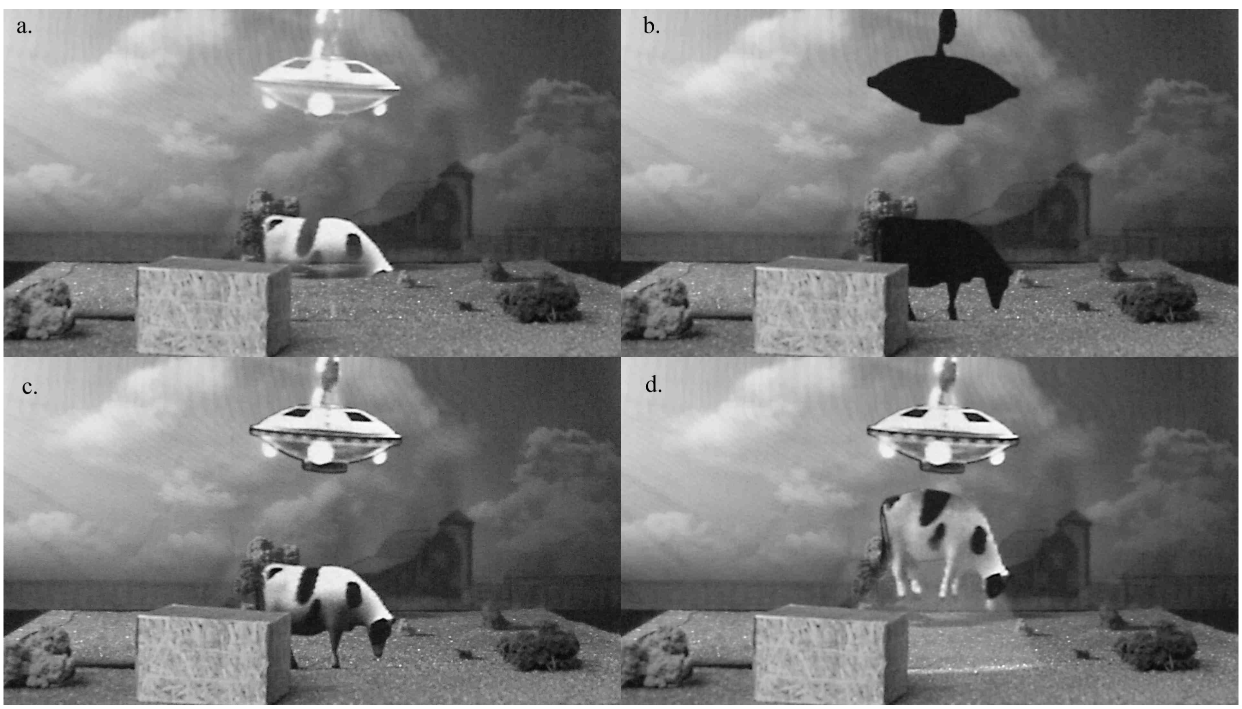

Figure 7a,b,c,d. Images of scrim projection with LCD mask.
a. Traditional scrim projection, b. LCD mask only,
c. Scrim projection with LCD mask, d. Another frame and viewpoint with occlusion and transparency

Figure 7a shows a traditional scrim projection of displaying one frame of an animated synthetic cow overlaid onto the physical set (with the LCD panel totally transparent). The synthetic cow is low contrast and semi-transparent with the backdrop and background props apparent. The physical foreground hay bale occludes the synthetic cow.

Figure 7b shows just the dynamic LCD masks of the UFO and cow overlaid onto the physical set. Notice the silhouettes are opaque and occlude the background trees and plate.

Figure 7c shows a scrim projection colocated with a dynamic LCD mask overlaid onto the physical set. Notice the synthetic cow is high contrast, opaque and occludes the background trees and plate.

Figure 7d shows a different viewpoint of the scrim projection with LCD mask. Notice the parallax between the downstage, center stage and upstage objects. The scene is inherently wide angle viewable.

4.4 Large LCD Masks

The aforementioned implementations of an LCD mask with either a beam-combiner or a scrim projection were prototyped using relatively small 25-27” diagonal displays. Although this size is sufficient for displaying small synthetic objects or for augmenting small dioramas, human sized synthetic characters are of interest, especially in entertainment and teleconferencing. Typically, such applications use Pepper’s Ghost or projection onto a static shaped projection screen. The former has all the drawbacks previously mentioned, typically being used against a dark background; while the latter has a static silhouette severely limiting the movement of the synthetic character.

We investigate implementing the LCD mask with a Pepper’s Ghost and scrim projection using larger human-sized LCD panels to provide larger characters with some freedom of movement that can be incorporated into a larger scene. Currently, the largest commercially available LCD panels are 90” diagonal, with 110” diagonal being available in mass-production in the near future.

a. 55” Pepper’s Ghost with LCD Mask

An upright 55” Dynex LCD television, modified by removing its backlight and diffuser, acts as a transparent LCD, a second 55” television cantilevered by a steel frame displays the synthetic color object, and a 4‘x6’ half-silvered mylar mirror (Hudson Mirror, LLC) acts as a beam-combiner. The transparent LCD is at the reflected image plane of the color display (Fig.8). A 4’x5’ backdrop of a radar station is mounted on foam core, placed 3½ feet behind the LCD panel and is lit by halogen floodlights.

Rendering and display of the color and mask animation sequences are similar to that described in §4.1 Beam-combiner with LCD Mask. The animation sequence consists of an alien spaceship hovering slowly and oscillating in height.

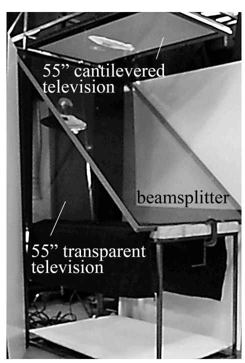

Figure 8. Setup for a 55” Pepper’s Ghost with LCD mask.

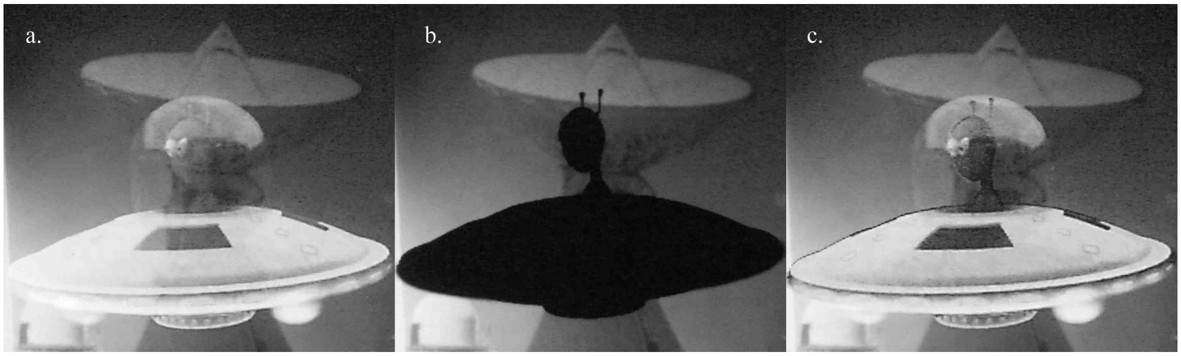

Figure 9a,b,c 55" Pepper's Ghost with LCD mask.
a. Traditional Pepper's Ghost, b. Mask only, c. Pepper's Ghost with LCD Mask

Figure 9a shows the original Pepper's Ghost effect (with the LCD mask off). The synthetic object is low-contrast and semitransparent. The background radio dish is apparent especially in the black panels of the spaceship.

Figure 9b shows the mask alone. There is no mask in the area corresponding to the transparent cockpit dome.

Figure 9c shows the Pepper's Ghost with the LCD mask on. The synthetic object is high contrast, and the spaceship is opaque except for the transparent cockpit dome.

b. 80" Scrim Projection with LCD Mask

An 80" Sharp Aquos 7 Series LCD television is modified by removing its backlight to act as a transparent LCD mask. The LCD panel is covered by scrim material (RoseBrand) and projected onto using a Panasonic SXGA+7000 DLP projector. A 48"x60" print is placed 3' behind the LCD panel, acting as backdrop, and is lit by halogen floodlights.

Figure 10 shows a physical human with a corresponding human sized synthetic character. Projection comes from the right of the image.

Figure 10. 80" Scrim projection with LCD mask.
[backdrop and prop textures intentionally mosaiced].

4.5 Transparent OLED with LCD Mask

A layered 2” transparent OLED display (uTOLED-20-G2, 4D Systems) and a 4” transparent liquid crystal panel from a mini projector (FAVI Entertainment) are stacked together (see figure 11). A globe and white card are placed 3” behind the display stack.

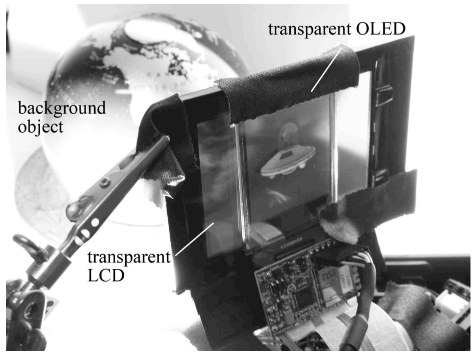

Figure 11. Setup of transparent OLED with LCD mask.

A prerendered color still of the alien spaceship is encoded for playback on the OLED display using the 4D Workshop IDE and stored on a microSD card. The image is automatically loaded and displayed on the OLED display when the microSD card is inserted into the display’s card slot. Using Quartz Composer running on a Macbook Pro laptop, a matching mask image is displayed on the Favi projector’s LC panel. The mask image is scaled, rotated and translated until the mask and color image are aligned.

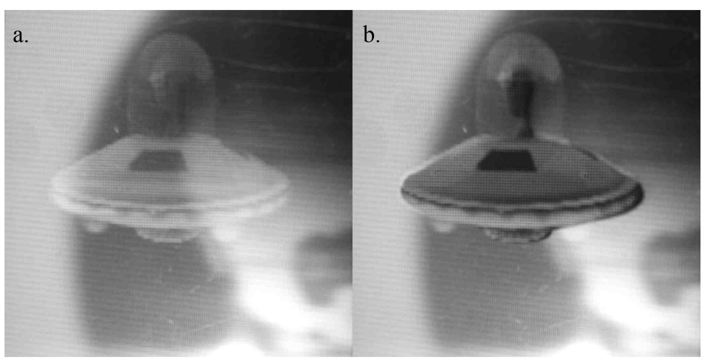

Figure 12a,b. Images of transparent OLED with LCD mask.
a. Transparent OLED against background object, b. Transparent OLED with LCD mask against background object.

Figure 12a shows the transparent OLED’s image (with the LC panel mask off) in front of a globe. The ship is low contrast and semitransparent. The continent on the globe is visible through the spaceship.

Figure 12b shows the transparent OLED’s image with the LC panel mask on in front of a globe. The synthetic spaceship is high contrast. The physical globe in the background is occluded by the synthetic spaceship except through the transparent cockpit dome where the edge of the continent is still visible.

4.6 Dual-Layer Transparent OLED with LCD Mask

To create dimensional synthetic objects, a second transparent OLED with a 1" thick clear acrylic spacer is placed in front of the existing transparent OLED with an LCD mask in §4.5 (see figure 13a). Depth antialiasing is be used to place opaque virtual pixels between the two scrims to produce continual apparent depth between the two planes (see figure 13b), similar to the multilayer display in §4.2. There is some Moiré interference between the two displays' pixels that changes with angle.

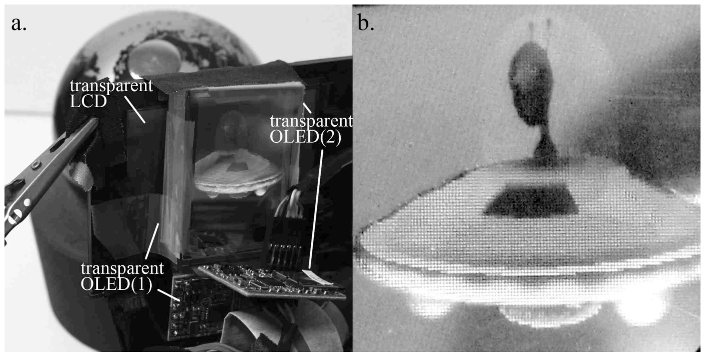

Figure 13a,b. Images of dual-layer transparent OLED with LCD mask.
a. Stacked dual-layer transparent OLED with transparent LCD panel, b. Dual-layer image with depth anti-aliasing and mask

5. RESULTS

5.1 Beam-Combiner with LCD Masks

The traditional Pepper's Ghost illusion (beam-combiner reflecting a display) results in semitransparent, low contrast images against bright detailed backgrounds, as seen in Figure 2a. The black panels of the space ship and the black spots of the cow are completely transparent, and even the shading of the underbelly of the cow allows the background to be visible. The silhouette mask in figure 2b occludes the background in areas the synthetic object is supposed to be opaque. With the color image reflection overlaid onto the mask, in figure 2c, the cow and space ship appear opaque, except the cockpit dome which is supposed to be transparent. The synthetic objects are high contrast and exhibit subtle shading, from the black of the ship's panels and cow's spots, to the shaded cow underbelly, to the white highlights in the cockpit dome. Synthetic objects may also be glowing and transparent such as the blue tractor beam in figure 2d, which is blue in the color image and clear in the mask. The masks do not need to be binary masks (black or white); they may be grayscale or even colored. Such masks act as neutral density or colored filters, respectively, of the background light.

By balancing the light levels on either side of the LCD panel, the set looks continuous. The split prop (the bush to the right of the cow) appears to pass through the plane of LCD panel, also helping to disguise the fact the LCD panel divides the set in half. Rendering the synthetic model with virtual lighting consistent with the real-world directional and global lighting leads to appropriate shading and highlights on the 2D image of the synthetic object that help it appear dimensional and visually integrated into the physical set. Although the images are prerendered, they can be easily rendered in real-time for interactive applications since only a color image and corresponding mask are needed by the display.

In figure 3a-d, a physical bale of hay prop is placed between the synthetic character and the beam-combiner. Because the bale of hay is behind the beam-combiner, the prop's image is combined with the reflected display's image and doesn't provide proper occlusion, as seen in figure 3a. Furthermore, the display's reflected image is visible but appears behind the prop in depth. By adding a phantom object in front of the reflected display, the color image is correctly occluded (figure 3b); so its reflection in the set by the beam-combiner looks correctly occluded as well (figure 3c). The phantom object is the same size and shape as the occluding prop but it is black and located at the corresponding position in the dual set (see figure 1); therefore occlusion/disocclusion by the prop occurs correctly for all viewpoints, multiple observers, and is independent of the synthetic object's location (see figure 3d). Notice that the change in viewpoint has revealed the cow's hind leg which was previously hidden behind the hay bale. Changes in viewpoint (see figure 3d), also produce proper parallax between the foreground, synthetic object, and background without headtracking.

Accommodation/focus cues are also produced naturally by the physical and synthetic objects at different depths. Motion parallax, accommodation, and occlusion/disocclusion are important 3D cues and must be self-consistent to provide a believable 3D scene. Unlike the LCD masks used by Kiyoshi in the HMD [3], these masks are located in the physical set and effectively mask the background for all views for many viewers without the need for goggles or head-tracking.

5.2 Beam-Combiner with Dimensional Display and LCD Masks

We use a multilayer display with the beam-combiner and LCD mask to add dimensionality and opacity (see figure 5b) to the traditional Pepper's Ghost illusion of displays (see figure 5a). When used with depth anti-aliasing to produce virtual pixels between the layers, the multilayer display produces images with apparently continuous depth, naturally coupled vergence/accommodation 3D cues, and some parallax. The multilayer display has a limited supported depth range between its two planes, but here it is only used to span the depth of the synthetic object not the depth of the entire set and scenery. Incorporating an autostereoscopic display into a larger physical set efficiently and effectively uses its limited depth range.

As observers change their viewpoints, there is correct parallax between the two layers. Although the multilayer display's depth anti-aliasing does become ineffective for significant off-axis views (see figure 5c-d), the usable field of view is about ±9° for our setup. At the edges of this range, the mask becomes apparent and the images are fuzzy but still dimensional (see figure 5c). This viewing angle is wide enough to provide a single casual viewer at arms length from the display some affordance for head movement to observe parallax in the scene, or two to three fixed viewers to get a sense of dimensionality. By ±16° off-axis, the images are completely misaligned and the character appears to be composed of multiple planes (see figure 5d). Compared with the display of §5.1, the use of the multilayer display produces dimensional synthetic objects at the expense of the field of view of the display.

Other types of autostereoscopic displays may be used in place of the multilayer display. Additional experiments were also performed using a lenticular based autostereo display (Alioscopy 3D HD 24" LV) in conjunction with a beam-combiner and LCD mask. Rather than using a physical phantom object, a synthetic phantom object (black textured 3D model) was included in the multiview color image to provide proper occlusion of the synthetic object by the physical foreground object. The resulting synthetic object was dimensional with occlusion effects but with a limited horizontal parallax and field of view (only 13.3° full angle), and depth (due to only supporting eight views). Again, the limited depth range, however only needs to encompass the synthetic character not the depth of the entire set and scenery.

Beyond the 13.3° field of view, on either side there is a small region of pseudoscopic imagery, then the eight views repeat again. After each pseudoscopic region, the synthetic object appears to make a discontinuous rotation following the viewer, back to its initial orientation. Furthermore, the image is horizontal parallax-only, so the view of the synthetic object does not change with the observer's vertical viewpoint. For both these reasons, the world orientation of the synthetic object in the physical set is therefore relative to the viewer's location, which can cause a misalignment in the color image and mask. This also causes inconsistencies between the synthetic object and the physical props and set; including incorrect alignment of the synthetic phantom object and its corresponding foreground object, resulting in incorrect occlusion. As with any lenticular autostereo display, accommodation and disparity are decoupled, which may lead to discomfort and inability to fuse stereo views, in contrast to the physical 3D scene the display is visually embedded in. For these reasons, we chose to concentrate on a multilayer display in this report, since it exhibits full parallax 3D, coupled vergence/accommodation cues, and a similar field of view and depth-range in this setup.

In addition to occluding the view of the background set, the LCD mask also blocks light from other light fixtures in the scene, and therefore casts true shadows (see figure 5b). These shadows also follow the animation of the mask and synthetic object, and movement of the light fixture without the need for any additional computation. In the present implementation, the transparent LCD panel greatly attenuates the spotlight illumination, so the illumination needs to be extremely bright and come from behind to cast noticeable shadows. Illumination from the front will cast shadows, but the projected light spot and shadow will be extremely attenuated and low contrast from the double pass through the transparent LCD panel (one pass for projection, a second pass for viewing). Implementations of the dynamic mask using other transparent/absorbing display technologies with less attenuation when transparent (e.g. transparent electrowetting displays) may result in more flexible lighting conditions to see shadows.

Although shadows are cast, they are only correct for a 2D planar object; they are not physically correct for a 3D object. Rather, they would be shadows of the 3D object's enface silhouette. For lighting nearly on-axis lighting (parallel to the LCD normal), the shadow will be approximately correct. While approximate shadows may be sufficient for many entertainment and interactive applications, if more accurate off-axis shadows are required, programmable lighting using a projector (à la Bimber [3]) could be used but a synthetic model of the scene would needed.

A beam-combiner with an LCD mask has several issues. Care must be taken to avoid warping in the beam-combiner (due to glass sagging under its own weight, or twisting of the mylar mirror's frame for example), which causes image distortion and may result in the color image and mask not being aligned for far off-axis viewing. Although phantom objects allow mutual occlusion with static foreground objects and the synthetic object, it is cumbersome to initially setup. Dynamic foreground real objects would need corresponding dynamic masks, be tracked and stay in one plane. The size of the mirror and additional dual set occupies much space. Scrim Projection and LCD Masks addresses these issues.

5.3 Scrim Projection and LCD Masks

Traditional scrim projection also produces low-contrast, semitransparent imagery against a bright background (see figure 7a). By including an LCD mask behind the scrim (see figure 7b), the scrim projection with an LCD mask produces high-contrast opaque objects with selective transparency (see figure 7c). Notice the transparent parts of the image (UFO dome and tractor beam) are clear in the mask (see figure 7b and figure 7d). Downstage (foreground) objects naturally occlude the scrim projection, so phantom objects are not necessary (See figure 7c). This means dynamic objects, including live actors may appear in front or behind the synthetic objects with appropriate mutual occlusion and without the need for tracking nor an updatable 3D model of the scene. There may be locations onstage where a dynamic object (potentially a live actor) may block the projection and cast a shadow, however this can be handled using multiple projectors to fill in any shadowed areas with appropriate content.

The projected imagery does not exhibit blow-by due to a combination of the mask and the natural attenuation from the LCD panel. The mask's role in removing blow-by will be more dominant when using alternate transparent/absorbing display technologies that have less attenuation when transparent (e.g. transparent electrowetting displays).

To create a dimensional synthetic objects using scrim projection with an LCD mask, a second scrim may be placed in front of the existing scrim [5] and LCD panel. Like the multilayer display in §5.2, depth antialiasing may be used to place virtual pixels between the two scrims for a limited field of view. The resulting dimensional imagery will have similar benefits and limitations as those previously discussed. Rear projecting onto the second scrim and front projecting onto the existing scrim may prevent cross-projection between the two scrims.

There is a small amount of reflection of the projected image off the LCD panel's glass; however because the projection is far off-axis the reflected image of the projector is not in the line-of-sight. Any reflection which may fall onto the stage is diffuse and dim (and reflected onto the back of props out of view). An interference based antireflective film (not antiglare diffusion film) applied to the LCD panel, such as used in "museum glass", may also significantly reduce any reflections.

Besides the additional texturing of the projected image and the slight softening of the background set typical of scrim projection, Moiré interference may appear between the scrim material and the LCD panel if the scrim is not taut and firmly against the LCD screen.

5.4 Large LCD Masks

a. Beam-Combiner

The upright transparent LCD display is approximately 2'3" tall and 4' wide, large enough for a small child or similar sized character. This size display also allows smaller synthetic objects to move in a larger environment, adding to the sense of integration with the physical environment. Here we display an alien ship hovering in front of the backdrop (see figure 9a-c). The backdrop is visible through the transparent cockpit dome with highlights (see figure 9c); notice the mask (figure 9b) is clear in the areas of the dome but is opaque in the areas of the alien and ship.

In a Pepper's Ghost illusion, the beam-combiner spans the entire set with its support frame hidden off-stage, so the reflected image can be seen anywhere on stage and from a wide field of view. However, the LCD panel's dimensions limit the size of the masked area. Either the set is the size of the LCD panel or the LCD panel must be incorporated into the set (e.g. doorway, window, etc). The set behind and in front of the LCD panel may be larger than the LCD panel. If the reflected image active area is larger than the LCD mask's active area, the synthetic character can appear to move beyond the LCD panel and onto the set wall.

a. Scrim Projection

Using an 80” diagonal LCD mask covered by scrim, the current setup is 3’4” wide and 6’ tall, tall enough for a seated human in ambient light against a brightly lit background, as seen in figure 10. The setup shown is in the landscape orientation, a legacy from a previous prototype and set. If the 80” LCD panel is rotated in portrait orientation, the scrim plus LCD panel would be large enough to hold even a tall standing human male. The landscape orientation could be used in a set where only the top of the human is visible, such as behind a desk; whereas, the portrait orientation may be used with the human in a doorway. The human is not confined to a single pose and has some freedom of movement and changing silhouette, while still having a brightly lit background appropriately occluded or visible.

Although Pepper’s Ghost and scrim projections have been used for live performances (e.g. Tupac at Coachella, Hatsune Miku concerts) and teleconferencing (e.g. Prince Charles at World Future Energy Summit), the synthetic characters were always against dark backgrounds. With the use of LCD masks, the synthetic characters can be placed in front of bright backdrops and scenery, increasing the appearance of being present and integrated into the local setting.

5.5 Single and Dual-Layer Transparent OLED with LCD Masks

Figure 12a shows that a plain transparent OLED display, although transparent and self-emissive, produces low-contrast semitransparent images. The entire globe is visible through the alien spaceship image. By combining the transparent OLED display module with a small transparent LCD module, we create a thin display that can controllably absorb or emit light to produce opaque high-contrast images on a transparent field, as seen in figure 12b. Because the display is absorbing and emitting light at the same location, there is naturally mutual occlusion with foreground and background objects. Also, there isn’t a chance that a dynamic foreground object will either be overlaid with the synthetic image (as in the beam-combiner case) or block the projection and cast a shadow (as in the scrim projection case). Ideally, a display panel with pixels that can absorb and emit light would be fabricated as one unit, so two separate displays would not have to be combined and aligned with possible Moiré interference.

The addition of a spaced second transparent OLED (see Figure 13a) and use of depth anti-aliasing to place opaque virtual pixels between the two OLED panels (see Figure 13b) adds several 3D cues – coupled vergence and accommodation cues, parallax, etc. – providing dimensionality to the synthetic character. It has similar drawbacks as the multilayer display with a beam-combiner of §4.2, especially a limited viewing angle before the separated planes become apparent. There is also Moiré interference between the two transparent OLEDs’ pixels that varies with angle. As these displays become larger, the combination of a transparent OLED (single or dual layer) with an LCD mask will provide a compact means of integrating high contrast, opaque synthetic characters into the physical world.

CONCLUSION

The three main techniques of integrating virtual objects into real-world settings – beam-combiners, scrim projection, and transparent OLED displays – have all been shown to produce semitransparent, low-contrast images against bright backgrounds. We have extended these techniques by including a dynamic mask, implemented using a transparent LCD panel colocated with the color images, to block the background and provide a black level. The combination of transparent/emissive displays with transparent/absorbing displays acts as an emissive display with a real-world alpha channel. The synthetic objects then appear opaque, high-contrast and may even cast shadows. The use of masks and color imagery in the physical set also allows synthetic objects to exhibit mutual occlusion/disocclusion, parallax, and accommodation cues with foreground and background physical objects. The synthetic character becomes an independent object in the scene. The mask and color image are colocated, staying aligned for all points-of-view, so the effect is viewable for multiple viewers without headtracking nor head mounted displays. We have also investigated using multilayer displays with depth anti-aliasing for implementing dimensional objects with natural parallax and consistent accommodation and vergence cues (at the expense of field of view). This use of multilayer displays is compatible with all three techniques, unlike using autostereo lenticular displays, for example.

This technique is not limited to using LCD panels to display the masks. LCD panels are currently limited in size, and greatly attenuate the light in their transparent state. Other transparent/absorbing displays with less attenuation in their transparent state, such as electrowetting displays, may also be used. With less attenuation in the transparent state, the masks will be even more important in creating shadows and blocking blow-by in projection arrangements. We are continuing to investigate technologies which will allow us to create larger scalable masks to possibly span an entire set. We are also continuing research in autostereoscopic displays and corresponding masks to create wider field of view 3D imagery compatible with this technique and to create more accurate shadows for off-axis lighting.

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