A Survey of 3-D Display Technologies

We are experiencing an explosion of interest in 3-D imaging in electronic displays, but no single 3-D technology is appropriate for all applications.

by Paul May

Charles Wheatstone, Fellow of the Royal Society and Professor of Experimental Philosophy at King’s College, London, demonstrated the first stereoscope to the Royal Society in 1838. It used combining mirrors to present separate images representing different perspectives of the same object to each eye (Fig. 1). By proving that stereoscopic perception relies on the fusion of two dissimilar and independent images, he ignited the Victorian passion for stereophotography. Autostereoscopic techniques that did not require the use of apparatus or glasses for viewing were first demonstrated by Frank Ives in 1903 by using parallax barrier techniques and Gabriel Lippman in 1908 by using microlens arrays.

Apart from the occasional 3-D movie that required the use of colored glasses, the advancement of 3-D visualization remained static until many of these early techniques could be applied to electronic displays in a practical way. Today, there is significant commercial interest in stereo 3-D for electronically driven displays, both in the generation of content and in the different techniques for displaying that content.

The availability of low-cost high-quality flat-panel displays has driven autostereoscopic techniques. This article will compare the different 3-D hardware configurations and their ability to address different application needs. It will also describe issues and techniques in 3-D content generation.

We will discuss four primary types of 3-D displays. The first is called a volumetric, or spatial, display. The remaining three types are all screen-based displays, and are split between stereoscopic displays requiring glasses and autostereoscopic displays that do not. Finally, autostereoscopic displays are further divided between dedicated 3-D displays and those that are reconfigurable, i.e., they can also be used as 2-D displays at the resolution of the base panel.

Volumetric Displays

Volumetric displays produce 3-D images in a three-dimensional volume. They can be observed without glasses by multiple users simultaneously, who can often literally walk around the image. These systems are by definition dedicated 3-D systems. Generally capable of showing transparent objects only, they trade off image complexity (the number of volume pixels, or “voxels,” in space and time) against performance (bandwidth of the display generator). These suggested applications include aircraft-collision avoidance, surgical visualization, and high-end engineering design.

As multiple viewers move around the transparent 3-D image of a volumetric display, they observe different views. Each of a viewer’s eyes sees a separate image and can be focused at different depths. The trade-off is cost and complexity. These displays are typically appropriate only for high-end professional and military markets in which a relatively limited number of transparent pixels gives useful depth information.

Volumetric technology approaches include stacked liquid-crystal-display (LCD) panels, electro-optic crystals, digital holography, and projection of images onto spinning screens. Stacked LCD panels require the projection of images at high frame rates onto electro-optic screens (usually LC materials) which can be switched between transparency and opacity. A sophisticated implementation of this technology is the DepthCube™ developed by LightSpace Technologies (Norwalk, Connecticut). Superficially, the DepthCube™ looks like a conventional monitor, i.e., a 2-D screen is viewed on one side of an enclosure. However, a true volumetric image with realistic parallax is seen.

Perspecta™, a system that has been commercialized by Actuality Systems, Inc. (Reading, Massachusetts), provides a 360° viewing angle by projecting the output from an image projector onto a 2-D spinning light-scattering plate (Fig. 2). This is a multiple-viewer walkaround display.

Holographic approaches that use very-high-resolution spatial light modulators as reconfigurable computer-generated holograms have also been reported.

StereoDisplay Displays

Stereo displays require the use of glasses, which decode and direct a different image from the 2-D screen plane to each eye. Most commonly, the glasses use switching shutters, polarization filters, or color filters. In the first of these approaches, the glasses are typically a pair of shutters (Fig. 3) synchronized with a fast scanning monitor. An example is CrystalEyes™, sold by Stereo-
Fig. 1: This stereo image pair is an illustration in Charles Wheatstone's paper on binocular vision published in 1838.

Graphics Corp. (San Rafael, California). This type of system has been suitable for CRT-based displays employing fast-response phosphors that provide high refresh rates. Such a technique is not suitable for standard LCD panels because of the relatively long response time of the liquid crystal within the panels.

Polarization-encoded displays use orthogonal polarizing glasses for the left and right eyes. They can use multiple, polarized projection displays, a patterned array of polarization rotators associated with the pixel array of a 2-D display, or a single polarization switch in front of a fast-response display operating at twice the image frame rate. In each case, alternate images — spatially or temporally — are rotated to an orthogonal polarization so that they are received by only one eye. When a viewer wears the polarization glasses, either half the resolution (spatially multiplexed) can be seen or the full display resolution presented at half the frame rate at which the 2-D display is capable (temporally multiplexed) can be seen.

Glasses using color filters (anaglyph) significantly degrade the color gamut of the original display, but are very inexpensive. The first multiple-viewer 3-D moving-image devices used the anaglyph approach, which has been largely replaced by polarization glasses for all but the lowest-cost applications.

Head-mounted displays (HMDs) provide another approach to stereo 3-D. In configurations providing a separate display for each eye, synchronized stereo pairs can be presented directly to a single viewer.

Because of the ability of stereoscopic displays (with the exception of HMDs) to allow multiple users to simultaneously view the same 3-D images, this approach has been used with particular success in projecting 3-D movies, so that an entire auditorium can share the 3-D experience. Multiple views, providing the ability to "look around" an image, are possible only for a single user whose position is determined by a head-tracking system. A great disadvantage is the need to wear glasses, which can be cumbersome for users.

Autostereoscopic 3-D-Only Displays

These displays do not require the use of glasses, and typically align additional optical elements, such as parallax barriers or lenticular screens, with the display to ensure that a viewer will see a different image with each eye (Fig. 4). These techniques have been known for about 100 years, but have come into their own for electronic displays with the emergence of large, high-resolution LCDs with lithographic placement of pixel positions and excellent flatness. Fixed 3-D autostereoscopic displays are generally designed for high-end professional markets, where dedicated single-user 3-D systems are justified.

These systems can be multi-view or head-tracked, i.e., they do not require a restricted viewing position, but there is a trade-off. The resolution of each image view decreases as the number of views increases; otherwise, the device cost rises substantially. Multiple-user viewing becomes possible with multi-view systems having nine or more views in which each view is blurred into the adjacent view to provide a displayed image that exhibits uniform intensity as the observer moves. The SynthaGram™ system developed by Stereographics Corp. is an example.

Three-dimensional images with quantifiably higher quality — less crosstalk, greater image depth, and higher resolution — can be obtained by combining a two-view display with high-quality optics. In these displays, the pixels of an LCD — and the black gaps between the pixels — are accurately imaged to the viewing zone of the display so that there is little mixing of the light from adjacent views, and there is therefore less crosstalk.

A key issue for the design of these displays is the trade-off between visibility of the resulting black bars between viewing positions and the quality of the 3-D image. The choice between a lower-quality multi-view display with greater viewing freedom and a higher-
3-D displays

quality two-view display with more-limited viewing freedom will likely be based on tested customer preferences and the specific application area.

Reconfigurable Autostereoscopic 2-D/3-D Displays
The most recent developments have been focused on allowing the 3-D effect to be switched off so that a display can be used both as a 2-D display or an autostereoscopic 3-D display. Most consumer applications do not require a dedicated 3-D system, and reconfigurability is key to providing a cost-effective solution when 3-D images will be viewed for a minority of the time and glasses are undesirable. Space constraints may also dictate the use of a reconfigurable screen in applications such as aircraft cockpits or in hospital operating theaters, where the 3-D mode can be useful in improved visualization but where a 2-D image display is also required.

Reconfigurable displays allow 3-D imaging to address high-volume markets on standard platforms, such as cellular telephones and laptops. The overwhelming majority of autostereoscopic 3-D displays that have been sold fall into this category. Reconfigurable parallax-barrier approaches require the production of a switchable, patterned absorption element in the 3-D mode, with a uniformly transmitting element in the 2-D mode.

The reconfigurable 2-D/3-D technology developed by Ocuity, Ltd. (Oxfordshire, U.K.) uses a polarization-activated microlens array, which is a passive birefringent microlens component index-matched with the adjacent layer for one polarization (Fig. 5). Consequently, one polarization approach results in a lensing effect, while the orthogonal polarization approach does not. A separate polarization switch determines whether the viewer sees the display through a lens component (for 3-D) or not (for 2-D).

We believe this approach is superior to that of actively switched LC lenses, which require high voltages, have slow switching response times, and have problems within the operating-temperature range. The passive-microlens approach enables the use of solid birefringent lenses for even greater stability, reduced component thickness (about 1 mm), and compatibility with high pixel densities.

From a performance point of view, both the parallax-barrier (Sharp Corp.) and lenticular (Ocuity, Ltd.) approaches should have similar cost profiles, with a projected cost of less than 20% of the base TFT-panel price. Both approaches can produce two-view and multiple-view 3-D images.

Although we are understandably enthusiastic about our own technology, we do believe that reconfigurable microlens arrays have several advantages over parallax barriers. Among these is that the 2-D transmission efficiency is maintained when switching into 3-D mode, rather than being reduced (typically by more than 50%) which is the case for parallax barriers.
barriers. They also demonstrate less crosstalk and thus provide greater lateral and longitudinal viewing freedom. At Ocuity, Ltd., we believe that these characteristics of microlens systems represent a significant advantage in mobile-display applications.

The applications for reconfigurable displays in cellular telephones, digital cameras, game consoles, DVD players, laptops, and desktops include

- 3-D gaming, for which stereo 3-D can provide the basis for completely new gaming experiences.
- 3-D photography and picture messaging, with stereo pictures created from one- and two-head cameras.
- 3-D visualization enhancement for education and entertainment.
- 3-D moving images converted from 2-D movies or live sporting events.

Software and Content Generation

There are three easy ways to generate the data required for screen-based 3-D displays. In computer graphics, the source data is typically in 3-D form within a digital model and is only flattened to 2-D to enable viewing on a standard display. In stereoscopic and autostereoscopic displays, two or more separate 2-D views can be rendered from the same 3-D graphics model and directed to the observer’s eyes. The total number of pixels in the display panel is unchanged from that in a standard 2-D panel, so the 3-D stereo bandwidth is typically a small increment compared to that of the standard 2-D image.

Volumetric displays typically require significantly higher computational bandwidth to achieve the equivalent spatial resolution because multiple planes of voxels at the required display resolution must be rendered. This tends to limit the practical spatial resolution of the engine for driving spatial displays—at least at a reasonable cost.

In the second method for generating 3-D data, purpose-built cameras—typically with two camera heads—are used to capture the 3-D data from a real scene. This approach, which has been used extensively for 3-D movies, has stringent tolerances on the alignment between the camera heads, and it becomes very difficult if more than a few views are required. However, software tools to automatically correct errors in camera alignment offer a promising route to reducing the cost of this method.

The third approach is to re-purpose existing 2-D content captured by a single camera. Here, the 2-D scene is analyzed to extract a depth map for objects in the image. From this map it is possible to produce a 3-D image data set that can be manipulated in a way similar to that of computer-graphics approaches.

This approach has been used to re-purpose images from 2-D still images in commercial products, although it can be difficult to extract depth information without introducing objec-
3-D displays

Fig. 5: Ocuity, Ltd., has developed a reconfigurable display with a polarization-activated microlens array that represents one approach to providing a single display that can be switched from (a) 2-D to (b) 3-D operation.

Fig. 6: There are many ways to create, format, and display stereo 3-D content, but all of them must take the requirements of the human cognitive system into account.
Table 1: Comparison of Stereo 3-D Approaches

<table>
<thead>
<tr>
<th>Typical System</th>
<th>Cost</th>
<th>Users/Views*</th>
<th>Unit Dimensions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric</td>
<td>$$$$</td>
<td>MU/MV</td>
<td>large</td>
<td>Transparent images only</td>
</tr>
<tr>
<td>Stereoscopic</td>
<td>$$</td>
<td>MU/2V</td>
<td>medium</td>
<td>3-D projection; requires glasses</td>
</tr>
<tr>
<td>Stereoscopic and head tracking</td>
<td>$$$</td>
<td>SU/MV</td>
<td>medium</td>
<td>Requires glasses</td>
</tr>
<tr>
<td>Autostereoscopic**</td>
<td>$$</td>
<td>SU/2V-MV</td>
<td>medium</td>
<td>Glasses-free, high end, low unit volume</td>
</tr>
<tr>
<td>(dedicated high end)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Autostereoscopic**</td>
<td>$</td>
<td>SU/2V-MV</td>
<td>small</td>
<td>2-D with 3-D option; high unit volumes</td>
</tr>
<tr>
<td>(reconfigurable)</td>
<td></td>
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</tbody>
</table>

*MU = multiple users, SU = single user, MV = multiple views, 2V = two views only.
**Head tracking for multiple views is also possible with two-view displays.

In all of the different ways in which stereo 3-D content is created, formatted, and displayed, the requirements of the human cognitive system must be taken into account to maximize the enjoyment and comfort to be obtained from 3-D stereo images (Fig. 6). Reports of visual strain from 3-D images can often be attributed to excessive image depth, poor left-eye/right-eye image alignment, high levels of display crosstalk (in which the left eye sees light from the right-eye image and vice versa), or mismatch between stereo and other depth cues (such as perspective, movement, and shading) in an image. Differences between accommodation and convergence visual cues in screen-based displays are also sometimes reported as possible causes of visual stress, but these may often be of secondary importance compared to the above-mentioned errors.

Summary

Unsurprisingly, there is no one 3-D approach that is suitable for all applications. For a multiple-user and multiple-view environment, one of the volumetric approaches is probably required, but their complexity and relatively high cost make them suitable for only the most demanding and specialized applications. Screen-based technologies that use glasses are probably best suited to applications in which multiple users share the same 3-D view on a large projection screen. Autostereoscopic systems are best suited to single users and can provide multiple views at the cost of reduced image resolution and 3-D image quality. They are most applicable to professional engineering applications. Finally, the most flexible approach is the reconfigurable autostereoscopic display, in which the stereo 3-D can be switched on and off and no glasses are required. This approach, with its superior price–performance characteristics, has the most promise for mass-market applications in which dedicated 3-D systems are not acceptable or in professional applications having other constraints, such as space and weight that preclude the use of a dedicated system (Table 1).

References