A full-time, full-resolution dual stereoscopic/autostereoscopic display
OR
Rock Solid 3D on a flat screen - with glasses or without!

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ABSTRACT

A stereoscopic or autostereoscopic display based on this technology provides full resolution and freedom of movement, but with no flicker. Simply put, the display is neither spatially nor temporally multiplexed. It sounds unbelievable, but it's true – an autostereoscopic display where each eye sees every displayable pixel on the screen at all times.

This technology is designed for flat-panel displays, such as LCDs and has the following characteristics:

- The display is not spatially multiplexed. Each eye sees the full native resolution of the entire screen.
- The display is not temporally multiplexed. The image for each eye is visible continuously, i.e., at all times.
- In its simplest form, this technology provides a full-time, full-resolution stereoscopic display for multiple viewers wearing passive polarizing glasses.
- A variation of this technology can be used to make a full-time, full-resolution stereoscopic projection system for viewers wearing passive polarizing glasses using just a single projector.
- With the addition of a dynamic aiming mechanism, and an adjustment in the display's output, we can create a single-user, full-time, full-resolution autostereoscopic display requiring no glasses and providing full freedom of movement. Software applications can use the same information about viewer position to provide natural, full "look-around."
- A hybrid version of the display can alternate between autostereoscopic (single-user, no glasses) and stereoscopic modes (multi-user, passive glasses).

Keywords: autostereoscopic display, stereoscopic display, 3D, Flat panel display, FPD, Liquid crystal display, LCD, projection, stereoscopic projection, 3D projection, look-around

1. INTRODUCTION

1.1. The "invisible display" re-visited

In an earlier paper[1], we introduced the concept of the "invisible display." A recap: Ideally, a display would be so like the real world that the viewer would not be able to distinguish it from reality. The "display" itself would be invisible – only the visual information would be apparent.

Display technology, both hardware and software, has been advancing in this direction, with increasing color depth, higher resolution, improved rendering, and speed. The photorealism sought in graphics displays 20 years ago has become the entry-level standard today.

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But photos are flat and the real world has depth. It has been well known for over a century that the most important cue for perceiving depth is stereo vision. Indeed, much effort is focused today on creating displays that mimic this aspect of the real world.[2]

So what are the characteristics of the ideal, "invisible", stereo display?

- High quality image with full-resolution. The 3D display should not compromise the viewer's expectations as established by current 2D displays. By contrast, any display that uses spatial multiplexing to achieve stereo (e.g., parallax barrier, parallax illumination, lenticular, micropolarizer regions) falls short of this requirement since it necessarily compromises the native, underlying display resolution.

- Rock solid image with no flicker. The display should look as solid and stable as real life. To achieve a rock solid image, each eye should have a "full-time" view of its image. A display that uses temporal multiplexing (field-sequential stereo) is susceptible to flicker, unless run at high switching speeds. Current mainstream technology for CRTs limits resolution as switching speed increases. LCD and other flat panel display technologies typically are not fast enough to support the high-speed switching requirements of sequential stereo.

  Thus, to provide the highest quality image, a 3D display should use neither spatial nor temporal multiplexing.

- Non-encumbering. The display should not require the viewer to wear special glasses or goggles. When looking at the display the viewer should simply see the visual information presented, just as she would when looking out a window or at a bowl of fruit.

- Freedom of movement with full look-around. In the real world, we gain additional information by moving and seeing the viewed objects from different angles. The ideal display should not constrain the viewer's movements, but rather encourage and exploit them.

1.2. Overview

In this paper, we show how to create a full-time, full-resolution flat panel display like that described above.

We start by showing how to build a flat panel display that provides a full-time, full-resolution display for one or more users wearing passive polarizing glasses. We then discuss how this technology can provide the mechanism for a passive-glasses-based, 3D projection system using a single projector.

Next we show how the flat panel display design can be modified and augmented to provide a single user with a glasses-free (i.e., autostereoscopic), full-time, full-resolution flat panel display with full freedom of movement and look-around capability. Lastly, we explain how a hybrid display can be built that will work in either mode: stereoscopic with passive glasses for many users or autostereoscopic for a single user.

2. PASSIVE POLARIZING GLASSES STEREOSCOPIC DISPLAY

2.1. The desired result

To best understand how this technology works, it's helpful to understand first what we're trying to achieve. Let's take a lesson from the movies.

The traditional way to show a 3D movie is use two projectors, corresponding to the two views (left & right). Each projector is fitted with a polarizing filter, with one filter orthogonal to the other. The viewers wear glasses with orthogonal polarizing filters, corresponding to the filters on the projectors. Thus each eye sees only the projected image intended for it while the other image is blocked.

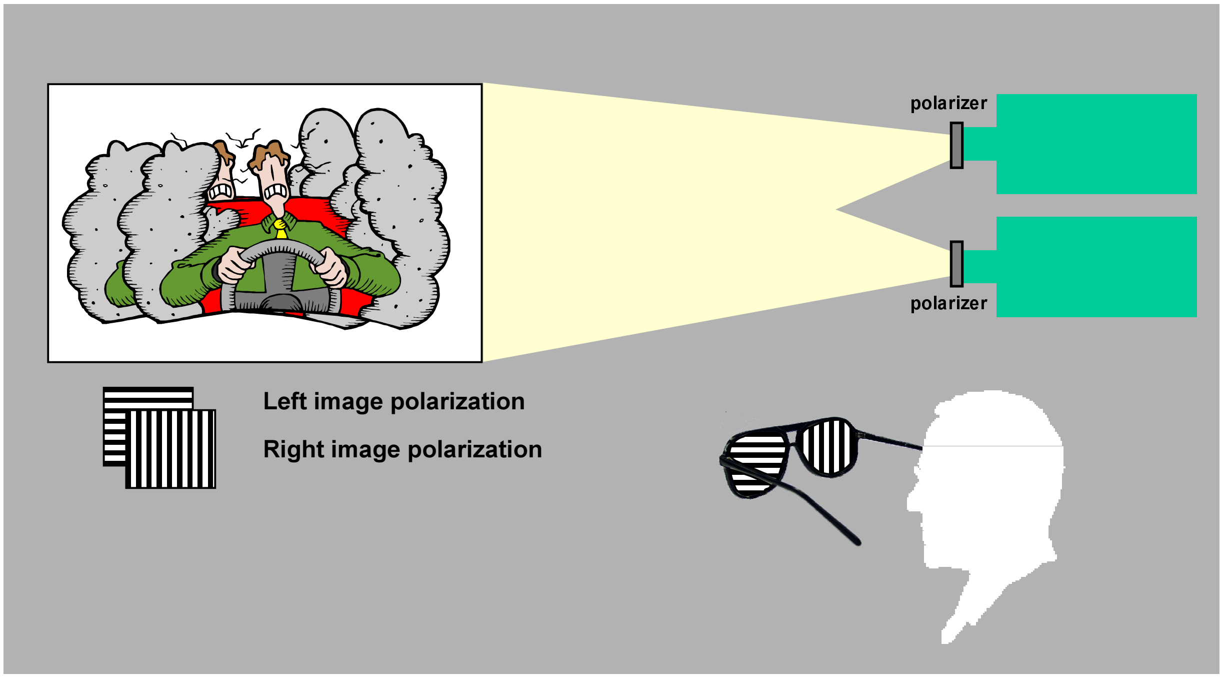

Figure 1. Traditional 3D projection with two projectors

But let's take a look at the projection screen. At any given point on the screen, light is being reflected (or for a back-projection-screen, transmitted) towards the eyes and that light comprises the light from both projectors.

However, we can also consider the composite of light originating from a given spot, by taking the vector sum of the contribution from each projector:

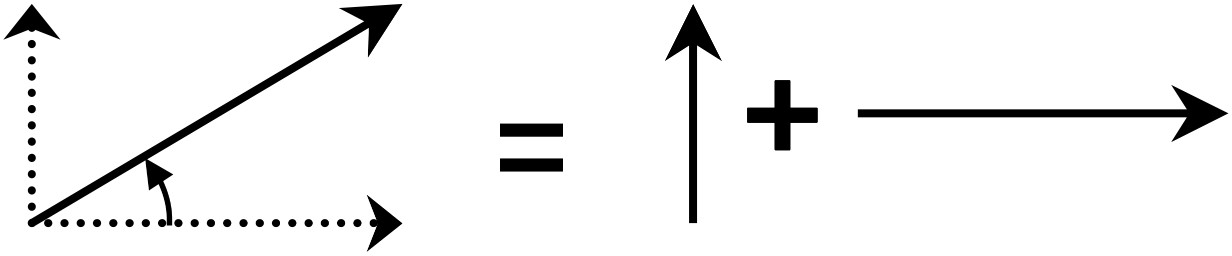

Figure 2. Light emanating from a given point is the vector sum of left & right projectors' contributions at that point

The filter on the viewer's right eye lets only the right component through, while the left eye's filter lets only the left component pass.

In our flat panel display, we are going to recreate this situation. Every pixel, indeed every sub-pixel, will display its information in such a way that each eye can see only what is intended for it. Since we're discussing here a situation where the user is wearing passive polarizing glasses, we want the sub-pixel to emit light polarized in one direction for the left eye and in the orthogonal direction for the right eye. As we've just shown, we can do that if we emit the light at the proper intensity and with a plane of polarization oriented such that the result is the vector sum of the left and right components.

In the following sections, we show how to do that.

2.2. Basic structure

For purposes of illustrating how to build a display with the required attributes, consider Figure 3. The display has two identical liquid crystal panels. Behind the panels is a standard backlight. The panel nearest the backlight is clad with polarizers in the usual fashion for making a conventional 2D LCD. The second liquid crystal panel has no polarizers.

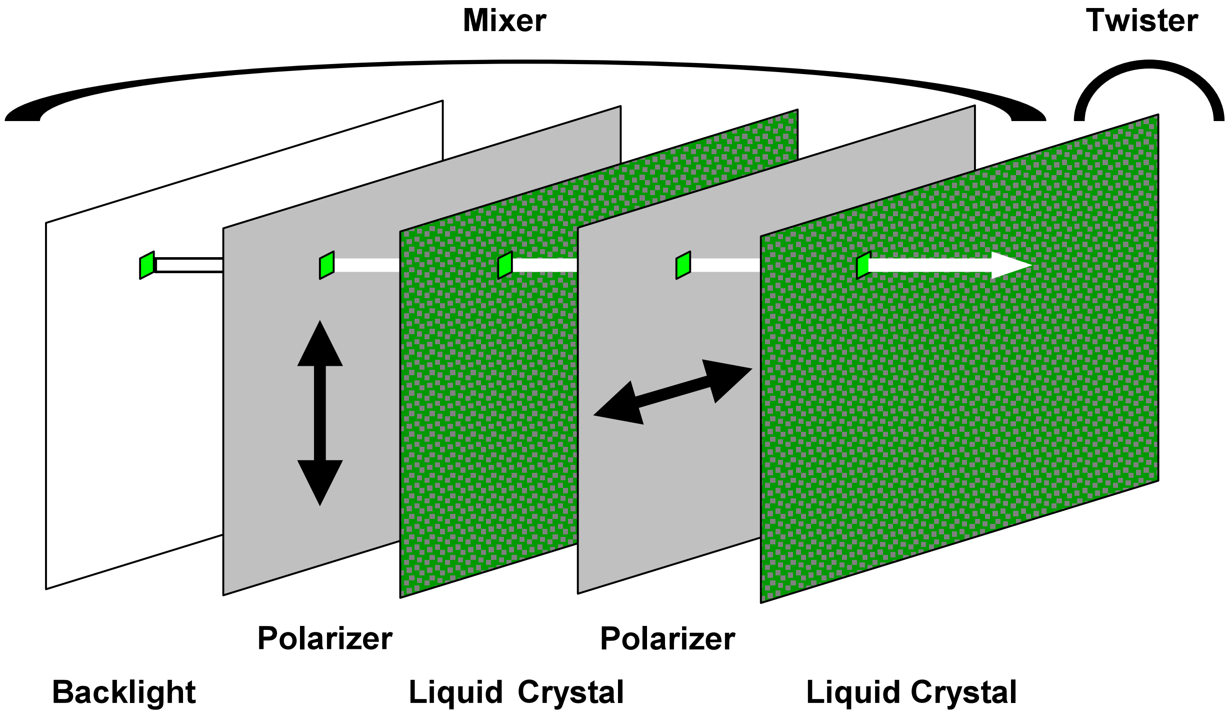

Figure 3. Block diagram of Mixer and Twister

The combination of backlight-polarizer-first LC panel-polarizer we call the *irradiance mixer*. The second LC panel is the *polarization encoder* or *twister*.

2.3. Irradiance mixer - creating a super sub-pixel

In the following sections, we will consider how these work by examining a single sub-pixel. For purposes of the discussion, we'll use the green sub-pixel located at coordinates [i,j], which we'll denote as $g[i,j]$. The corresponding sub-pixel from the left image is denoted by $g_L[i,j]$ and the from the right image, $g_R[i,j]$In our display, we need the sub-pixel at [i,j] to display with a "combined" intensity representing the contributions of both the left and right images at that location. Continuing the notation introduced above, we'll call the combined sub-pixel $g_C[i,j]$. Thus the total irradiance at each sub-pixel will be an "average" of the sub-pixels' irradiance of each image, normalized to stay within the range of the display's capabilities. While we call it "average", the new intensity is *not* the arithmetic mean of the two contributing sub-pixels' irradiance. The actual function used will depend on various characteristics of the first and second panels. For purposes of this discussion we will refer to the function that calculates the resultant irradiance as *mix(L, R)*. Thus:

$$g_C[i,j] = mix(g_L[i,j], g_R[i,j])$$

We now have a sub-pixel that contains the composite brightness of both left and right images, or a *super sub-pixel*.

Note that the output of the mixer is uniformly polarized across the entire image in the same direction as the output (or analyzer) polarizer. Figure 4 shows an example of the image output from the mixer with a sample left-right image pair.

Figure 4. Mixer output with sample stereo pair input

2.4. Twister – encoding the super-sub-pixel with polarization

The light from the super sub-pixel then passes through the next liquid crystal panel. This panel's function is to turn the plane of polarization for that sub-pixel, such that the resultant component vectors correspond to the original left and right images' respective contributions. In other words, we must turn it an angle θ, such that the resultant component vectors' intensities will correspond to the original input intensities, i.e.,

$$g_L'(i, j) = g_C(i, j) \sin \theta$$

$$g_R'(i, j) = g_C(i, j) \cos \theta.$$

The illustration below (Fig. 5) shows an example of the twister encoding with the same sample left and right image pair as above. Note that to make the encoding visible, it is shown with crossed polarizers – in practice, the twister always appears transparent to the unaided eye.

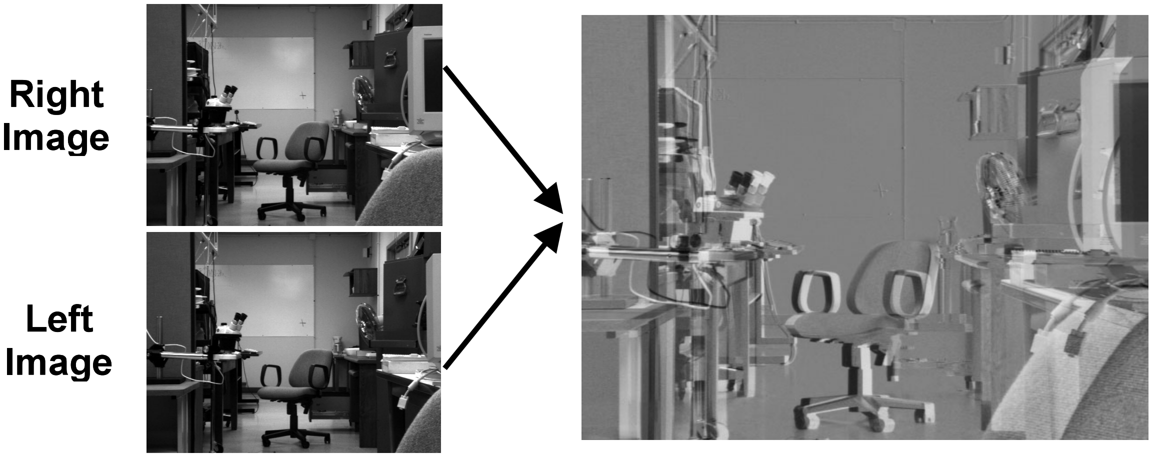

Figure 5. Twister output with sample stereo pair input (shown with crossed polarizers)

Once the light has passed through both layers, the effective result is the same as if it had originated with two projectors in our traditional 3D theater example above. Appropriate orthogonally polarized filters over the viewer's eyes (i.e., standard passive polarizing glasses) provide a 3D viewing experience. Each eye sees only the appropriate image over the entire screen, at full resolution, the entire time.

2.5. Single-projector stereo

Having achieved a full-time, full-resolution flat panel display that mimics the experience 3D movie-goers have enjoyed for over fifty years, it is only fitting that we take our solution and adapt it back to the movie theater.

Until now, 3D projection has traditionally been done using two projectors, each showing the view for one eye and fitted with a polarizing filter corresponding to the filters in glasses worn by the viewers. We've shown in the previous sections how an LCD assembly can provide the same effect on an LCD display.

A projector can be built using the same techniques as the above-described display. By sending light through a mixer LC panel and then a twister LC panel, we can project the resulting image onto a polarization-preserving screen. That image can be viewed through traditional passive polarizing glasses and will provide the same high-quality 3D experience as the traditional two-projector solution. However, since only one projector is required, it can be done at a fraction of the cost, not to mention being considerably easier to set up and use. Such a projector is suitable not only for the moviegoer, but also design centers, conference rooms, home theaters, and the living room.

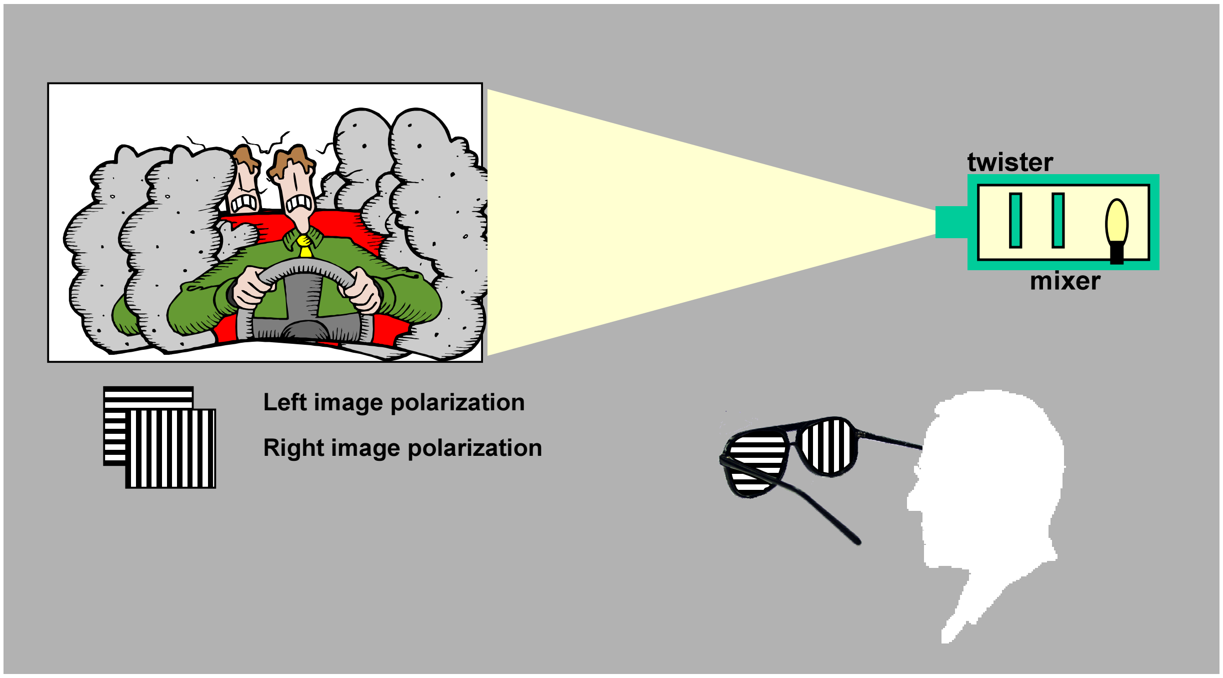

Figure 6. Single-projector 3D projection system

3. LOSING THE GLASSES – AUTOSTEREOSCOPIC DISPLAY

3.1. Introduction

So far we've shown how to build a stereoscopic display providing full resolution (i.e., no spatial multiplexing) and no switching (i.e., no temporal multiplexing). However, it still requires the viewer to wear special eyegear to view 3D. In this section we'll show how a modified design can be used to provide the same benefits outlined above, but in a single-user, autostereoscopic version – i.e., no special eyegear required.

3.2. Figures

In the following figures, the scene is viewed from above. The display is shown at the right of the figure. Light travels "right-to-left" from the display towards the viewer's eyes at the left side of the figure.

Polarized light and polarizing filters are represented in the drawing by vertical or horizontal hatching. When polarized light encounters a polarizing filter, it passes through a region of matching polarization and is blocked by a region with orthogonal polarization.

For illustration purposes, the left-eye and right-eye images are shown as if they originate from separate layers in the twister. However, as explained above, they are actually the vector sum of the two images' respective polarizations and emerge coincident from the display. For simplicity's sake, the two are shown as separate layers in the figures, each with its corresponding polarization.

3.3. Basic geometry – twisting for autostereo

In the system described above, we have assumed the viewer is wearing passive polarizing glasses. The aggregate effect of the mixer and twister is to provide an entire left-eye image with one polarization and an entire right-eye image with the orthogonal polarization.

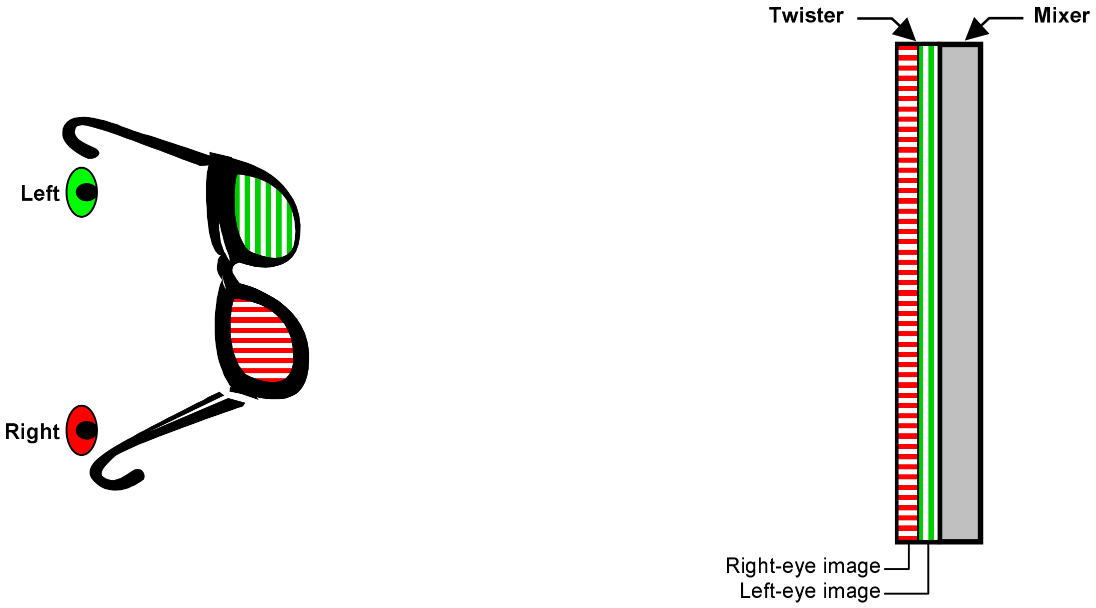

Figure 7. Review of glasses-based full-time, full-resolution 3D flat panel display

To create an autostereoscopic display, we start by changing the output of the twister. Rather than providing uniform polarization for each eye's image across the entire screen, we create vertical striped regions across the display. Each region shows a vertical portion of the left image polarized in a first orientation and a portion of the right image polarized in a second, orthogonal orientation. Its neighboring regions show a portion of the left image polarized in the second orientation and a portion of the right image polarized in the first orientation. Thus, for example, if the left image light is oriented horizontally in the first, third, and fifth regions and vertically in the second, fourth and sixth regions, then the right image light will be oriented vertically in regions 1,3, and 5 and horizontally in regions 2,4, and 6. This new polarization pattern of the twister is illustrated in Figure 8.

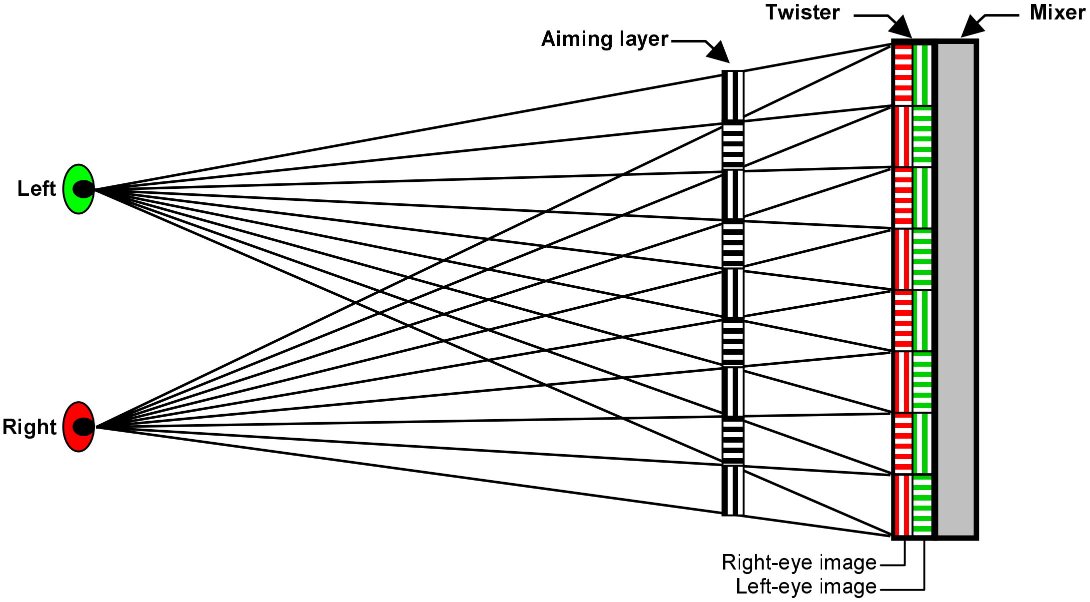

Figure 8. Autostereoscopic full-time, full-resolution 3D flat panel display

Once we have created this arrangement, we can introduce the aiming layer as shown in Figure 8. The aiming layer is composed of vertical striped regions of passive polarizing filters, where the plane of polarization of each region is orthogonal to its neighbor. As can be seen by following the light paths from each region to the eyes, the filter will pass the light intended for the appropriate eye while blocking the light intended for the other eye.

Thus, the configuration shown in Figure 8 provides a full-time, full-resolution flat panel display viewable without special glasses. But we're still not done yet.

3.4. Eliminating the sweet spot – dynamic aiming

As described thus far, this display suffers from a "sweet spot" – a fixed position from which the viewer must not move, lest her eyes experience cross-talk, i.e., seeing light from the inappropriate image.

To overcome this problem, we require

1) a mechanism to locate the position of the eyes in space, and
2) a means to dynamically adjust the geometry of the system to accommodate the eyes' new position.

It is beyond the scope of this paper to describe the mechanism by which the eyes are located. It is sufficient to note that there are various methods for determining this, including several that are commercially available. The twister and aiming layer can use the information from the eye-location finder to dynamically adjust the geometry. It is to this *dynamic aiming* process we now turn our attention.

In our discussion so far, we have assumed the aiming layer is constructed of static polarized filtering stripes. If, however, we construct those layers with a uniform polarizer and a finely divided, "micro-striped" liquid crystal, we are able to adjust the position and size of the stripes at will and in concert with the striped output from the twister. In this way we dynamically alter the geometry to match the position of the viewer's eyes. For example, lateral motion of the viewer requires corresponding lateral adjustment of the stripes. If the viewer approaches the display, the stripes would get wider. More complex configurations are sometimes required (e.g., when a viewer turns her head) and are possible with this approach.

The mechanism for this is essentially the same as that described for constructing an autostereoscopic, field-sequential display with full freedom of movement[1], to which the reader is referred for a detailed discussion.

It is important to note that the same data provided by the eye-location finder to the aiming mechanism can also be supplied to an appropriately programmed application to present a viewpoint-appropriate image ("look-around"). Look-around is an important aspect of simulating the real world.

3.5. Hybrid display

In real-world applications, a user of a 3D display is likely to work alone for extended periods of time, interspersed with periods of collaboration with colleagues. When working for extended periods, an autostereoscopic display is preferable. But an aiming, autostereoscopic display such as the one described here can only be used by a single user. Enter the hybrid display.

In the autostereoscopic display described above, the hardware change from the passive-glasses stereoscopic display is the addition of the aiming layer and the change in twister behavior (under software or firmware control). By simply disabling the aiming mechanism, the display can revert to being a multi-user stereoscopic display.

Thus our user described above can work for hours in the comfort of full autostereo. When the need for one or more colleague's input arises, the display can be switched, all viewers don passive polarizing glasses and the same display meets the needs of the collaborating group.

3.6. Conclusion

In this paper we've shown how to build a display that will provide a rock-solid 3D image. It's "rock solid" because it uses the full native resolution of the display for each eye (no spatial multiplexing) and each image is visible at all times (no temporal multiplexing). This full-time, full-resolution display can be implemented in a flat panel display or in a single-projector projection system. As a flat panel display, it can be implemented in a multi-user, passive-glasses form, a single-user, autostereoscopic (no glasses) form, or in a switchable hybrid display that does both.

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