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Demonstration of a novel three-dimensional autostereoscopic display

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We report what we believe is the first static implementation of the partial-pixel architecture, which provides a conceptual framework for the construction of real-time three-dimensional displays that are functionally equivalent to holographic stereograms (i.e., the simultaneous display of a series of stereoscopic images). The device is physically realized as a set of amplitude diffraction gratings on a chrome mask that was fabricated by standard photolithographic techniques. The intended three-dimensional object encoded in the display was strikingly visible on readout with an incoherent illumination source.

Real-time holographic display archectures are currently of significant interest,[1-3] in part because of intense international competition to develop advanced displays for high-definition television, three-dimensional (3-D) workstations, and virtual reality systems. We recently invented an alternative approach to holographic displays for such applications. Our 3-D display architecture (referred to as the partial-pixel architecture) is functionally equivalent to a holographic stereogram yet lends itself to real-time implementation by use of liquid-crystal technology.[4,5] In this Letter we demonstrate the visual feasibility of our approach, using a partial-pixel-architecture-based device that displays a fixed 3-D scene.

The basic geometry for our display concept is illustrated in Fig. 1. A pixelated display is present in the $x-y$ plane, and a viewing region is located a distance d_v from the plane. One can think of the viewing region as a series of adjacent virtual slits that are approximately one pupil diameter wide. As in a holographic stereogram,[6] each eye of an observer sees a different image on the display. When the appropriate set of stereopair images is simultaneously presented on the display (with a single image visible through each virtual viewing slit) the scene appears 3-D. In addition, the display can exhibit one-dimensional motion parallax, as an observer moves his or her head from side to side within the viewing region. Since special headgear is not required to view the display, it is also autostereoscopic.

As an example, consider the display of a 3-D scene composed of the letters U, A, and H. As illustrated in Fig. 2, the plane of the U is in front of the plane of the A, while the plane of the H is behind the plane of the A. If this 3-D scene were displayed by use of the geometry described above, the left eye would observe the two-dimensional (2-D) image shown in Fig. 3(a) when (for example) looking through virtual viewing slit m, while the right eye would see the 2-D image shown in Fig. 3(b) through virtual viewing slit m′ (which is one eye separation away from virtual viewing slit m). An observer would perceive these separate 2-D stereopair images as the single 3-D image shown in Fig. 2. If additional appropriate stereopair images were displayed through the other virtual viewing slits, one-dimensional motion parallax would be exhibited, as an observer's head traversed the viewing region. In each 2-D image shown on the plane of the display this would be manifested as an apparent change in the relative position of the letters with respect to one another.

For the separate images to be displayed simultaneously through each virtual viewing slit, each pixel of the display must (1) direct light into each virtual viewing slit and (2) independently control the amount of light directed to each virtual viewing slit. A pixel fulfilling these requirements could thus appear to be on (i.e., bright) when viewed through virtual viewing slit m, while simultaneously appearing to be off (i.e., dark) when observed through virtual viewing slit m + 1.

In the partial-pixel architecture we achieve these pixel requirements by subdividing the area of each pixel into smaller regions (i.e., partial pixels). Since the display is designed so that the size of each pixel is at the resolution limit of an eye in the viewing region, these partial pixels are not visually distinguishable. Each partial pixel is responsible for directing light into a single virtual viewing slit as well as for

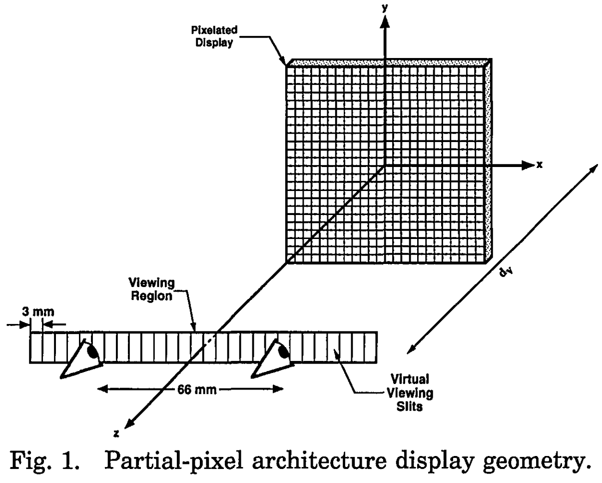

Fig. 1. Partial-pixel architecture display geometry.

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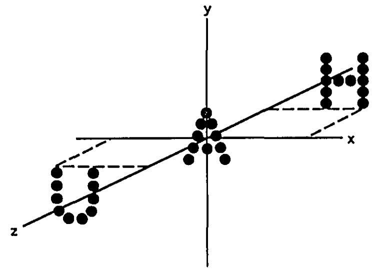

Fig. 2. Example 3-D scene in which the letters U, A, and H are represented as a series of dots.

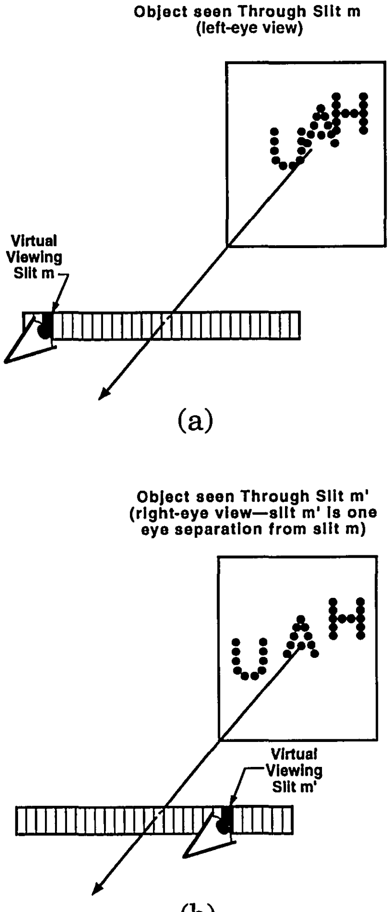

Fig. 3. Schematic representation of (a) left-eye and (b) right-eye images as seen through slits m and m′, respectively.

controlling how much light is directed toward that slit. Construction of a display that operates like a holographic stereogram is thus reduced to the implementation of partial pixels that provide this basic functionality.

Although there are many methods of physically realizing such partial pixels, our demonstration device makes use of a simple technique in which each partial pixel is composed of a single diffraction grating. Each grating is designed to diffract its +1 order to the appropriate virtual viewing slit. For a partial-pixel display that is backilluminated by a collimated beam, the grating in each partial pixel has a period of[5]

$$\Lambda_{ijm} = \frac{\lambda}{[(\alpha_{ijm} - \alpha)^2 + (\beta_{ijm} - \beta)^2]^{1/2}} \tag{1}$$

and an angular orientation (i.e., the angle between the grating wave vector and the x axis) of

$$\theta_{ijm} = \tan^{-1}\left(\frac{\beta_{ijm} - \beta}{\alpha_{ijm} - \alpha}\right), \tag{2}$$

in which α and β are the x- and y-direction cosines of the incident readout beam, α_{ijm} and β_{ijm} are the x- and y-direction cosines of a vector from the center of the mth partial pixel of the ijth pixel to the center of the mth virtual viewing slit, and λ is the wavelength of the readout beam.

To demonstrate the partial-pixel method of image formation, we chose to display the 3-D scene of Fig. 2, using a set of amplitude gratings fabricated on a 4-in. (10-cm) chrome mask. The viewing region was designed to be 200 mm from the mask when illuminated by a 633-nm collimated beam (the readout geometry is illustrated in Fig. 4). The maximum angular range of the viewing region was ±13.5° from the z axis. The angular viewing range is constrained by the minimum feature size on the chrome mask, which in our case was 1.1 μm. Larger angular viewing ranges are anticipated in future devices that use smaller feature sizes.

The design of the readout geometry and the partial-pixel gratings was such that all diffraction orders except the appropriate +1 orders fell outside the viewing region. Thus there was no cross talk within the virtual viewing slits that was due to higher diffraction orders from any of the gratings.

As described in Ref. 5, diffraction from the aperture of each partial pixel is used to define the spatial

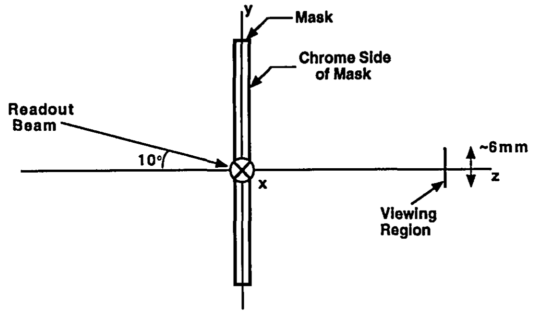

Fig. 4. Schematic of the mask readout geometry.

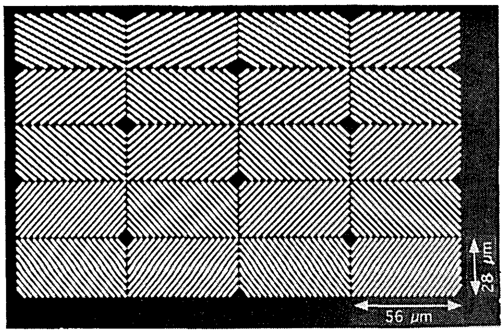

Fig. 5. Single display pixel that consists of a set of 20 partial-pixel gratings.

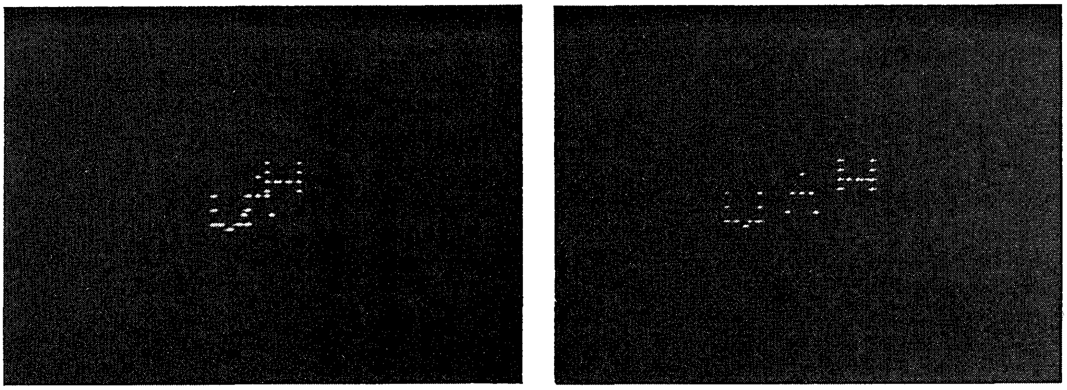
(a) (b)

Fig. 6. Photographs of sample (a) left-eye and (b) right-eye images generated by the mask display.

extent of the virtual viewing slits. For this chrome mask device there were 20 virtual slits, each nominally 3 mm wide and 6 mm high.

The display region was 1 cm × 1 cm and was composed of a 35 × 35 array of pixels that were 280 μm × 280 μm in size. Each pixel consisted of a 4 × 5 array of partial pixels, each of which was 28 μm × 56 μm. The partial-pixel gratings for a single pixel are shown in Fig. 5. This particular pixel encoded one point of the letter A, which was designed to appear in the plane of the display. Hence there is a grating in each of the 20 partial pixels because this pixel must appear on from each of the 20 virtual viewing slits.

To read out the display we used a small flashlight (a Mini-Maglight manufactured by Mag Instrument, Ontario, Calif.) with a red photographic filter (which acted as a short-wavelength cutoff filter at 620 nm). The built-in collimating adjustment of the flashlight was used to quasi-collimate the readout beam. We found that the degree of collimation of the flashlight and the precise angle of incidence of its illumination were not critical to the successful viewing of the display.

When an observer placed his or her eyes in the viewing region, a clear 3-D image was observed. Typical left- and right-eye images are shown in Figs. 6(a) and 6(b), respectively (many readers may be able to fuse these 2-D photos into a 3-D image). Approximately 200 people successfully viewed the device at the October 1993 Society for Information Display/IEEE Active Matrix Liquid-Crystal-Display Symposium in Lehigh, Pa.

One-dimensional motion parallax was also discernible in the device when an observer's head moved horizontally across the viewing region. The effect was not pronounced because the angular viewing range was relatively small, the stereopair images were not selected to exaggerate the amount of apparent object rotation, and the readout illumination was not highly collimated. Future displays can be easily designed to show more striking one-dimensional motion parallax in conjunction with a more-collimated readout beam.

In summary, we have demonstrated a static 3-D display based on the partial-pixel architecture. A 3-D scene was encoded as a set of amplitude gratings in a chrome mask and successfully viewed by a wide range of individuals. We are now pursuing real-time implementations of the partial-pixel architecture, using a variety of techniques, including diffraction gratings in liquid crystals.[7]

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