Image Tiling for a High-Resolution Helmet-Mounted Display

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ABSTRACT

Head-mounted or helmet-mounted displays (HMDs) have long proven invaluable for many military applications. Integrated with head position, orientation, and/or eye-tracking sensors, HMDs can be powerful tools for training. For such training applications as flight simulation, HMDs need to be lightweight and compact with good center-of-gravity characteristics, and must display realistic full-color imagery with eye-limited resolution and large field-of-view (FOV) so that the pilot sees a truly realistic out-the-window scene. Under bright illumination, the resolution of the eye is ~300 μr (1 arc-min), setting the minimum HMD resolution. There are several methods of achieving this resolution, including increasing the number of individual pixels on a CRT or LCD display, thereby increasing the size, weight, and complexity of the HMD; dithering the image to provide an apparent resolution increase at the cost of reduced frame rate; and tiling normal resolution subimages into a single, larger high-resolution image. Physical Optics Corporation (POC) is developing a 5120 × 4096 pixel HMD covering 1500 × 1200 mr with resolution of 300 μr by tiling 20 subimages, each of which has a resolution of 1024 × 1024 pixels, in a 5 × 4 array. We present theory and results of our preliminary development of this HMD, resulting in a 4k × 1k image tiled from 16 subimages, each with resolution 512 × 512, in an 8 × 2 array.

Keywords: Head-Mounted Display, Helmet-Mounted Display, Eye-Limited Resolution, High-Resolution Display

1. INTRODUCTION

Physical Optics Corporation (POC) is developing a superhigh resolution miniature head/helmet mounted display (HMD) based on a commercially available high-speed microdisplay and a nonmechanical digital scanner. By "superhigh" resolution we mean that the display resolution is greater than the resolution of the viewer's eye, which is generally accepted to be 2 arc-min/pixel pair[1]. Pilot training and mission simulation is effectively photorealistic with superhigh resolution wide field-of-view HMD imagery.

In an attempt to satisfy the resolution requirement of 2 arc-min/pixel pair (or 1 arc-min/pixel), current developers have taken two extreme approaches[2]: increase the pixel count of a standard miniature 2D display (scene generator) such as a liquid crystal display (LCD), or use three laser beams (one each red, green, and blue – RGB) to write a 2D image by high speed modulation and scanning. Neither approach can readily achieve superhigh resolution in a lightweight, head-mounted design. An LCD with such high resolution is far beyond the current limit of reliable chip manufacturing technology, while for a laser-scanned display the required resolution demands scanning speed far beyond that of current scanner technologies, including microelectromechanical systems (MEMS), which introduce problems such as the beam spreading that is due to the instability of micromirrors at high scanning speed[3].

To overcome these difficulties, POC is developing a HMD based on image tiling, an approach that has previously been adopted in large size, high-resolution display systems[4]. Instead of increasing the resolution of the scene generator, the image is tiled into a number of subimages. Each subimage is sent through the high-speed tiling optics, which are based on standard miniature optical components. By doing this we break down the problem of transmitting a 5 kpix × 4 kpix, 84° × 67° image—at a data rate of 600 Mpix/s for 30 frames/s—to generating 20 1 kpix × 1 kpix images (data rate 30 Mpix/s) and tiling these images together (tiling rate of 600 subimages/s). In addition to studying this method of enhancing displays, we fabricated a subscale version, a 4 kpix × 1 kpix tiled-image display comprising 16 subimages in an 8 × 2 array. The output of this prototype is shown in Fig. 1.

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Fig. 1. Sixteen subimages tiled into a single image for a high-speed, high-resolution HMD.

2. DESIGN OF THE 5 KPIX × 4 KPIX DISPLAY

Design issues for the development of a HMD with wide field-of-view (FOV > 80° × 65°) and eye-limited resolution are discussed below. The maximum resolution of the eye is ~1 arc-min and eye movements are not expected to exceed the specified FOV when an HMD is in use.

2.1. Resolution, Field-of-View, and Color

For the resolution of a wide FOV device to be eye-limited (2 arc-min/pixel pair), the input image resolution (number of pixels along the corresponding direction, horizontal or vertical) must be high. The interrelationship among the input image resolution (number of pixels across the measured dimension), the FOV, and the angular resolution of the image seen by the eye, shown in Fig. 2, obeys the equation

$$res = \frac{FOV}{npix} \quad , \tag{1}$$

where *res* is the resolution, *FOV* is the overall field-of-view, and *npix* is the number of pixels. All three variables are measured in the same direction. Eq. (1) tells us that, for example, with an input image with 4000 pixels, a 66° FOV allows eye-limited image resolution, whereas for a 100° FOV the image resolution is reduced to 3 arc-min/pixel pair, 50% worse than the eye limit.

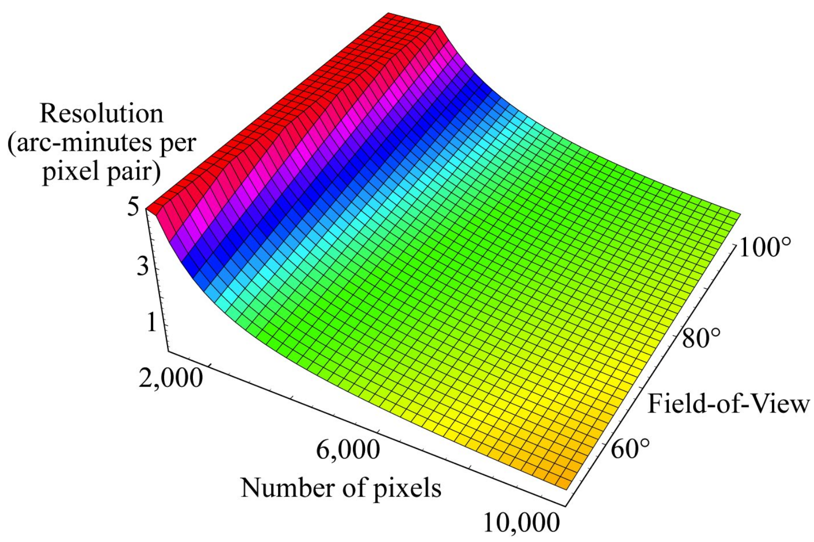


Fig. 2. Resolution as a function of number of pixels (in one dimension of the display) and Field-of-View.

To achieve the goals stated above—80° × 65° FOV and resolution better than 2 arc-min/pixel pair—requires a display with at least 4800 × 3900 pixels. A convenient tiling method is to combine 20 subimages, each 1 kpix × 1 kpix, in a 5 × 4 array.

Adding color to such a display increases the complexity enormously. The simplest method of adding color uses the same scene generator for each image, whether red, green, or blue, and changes the illumination. Then successive frames are different colors. Another way to look at this is that each subimage is broken down into its RGB primary colors, so successive images within a frame are different colors (see timing diagram, Fig. 3).

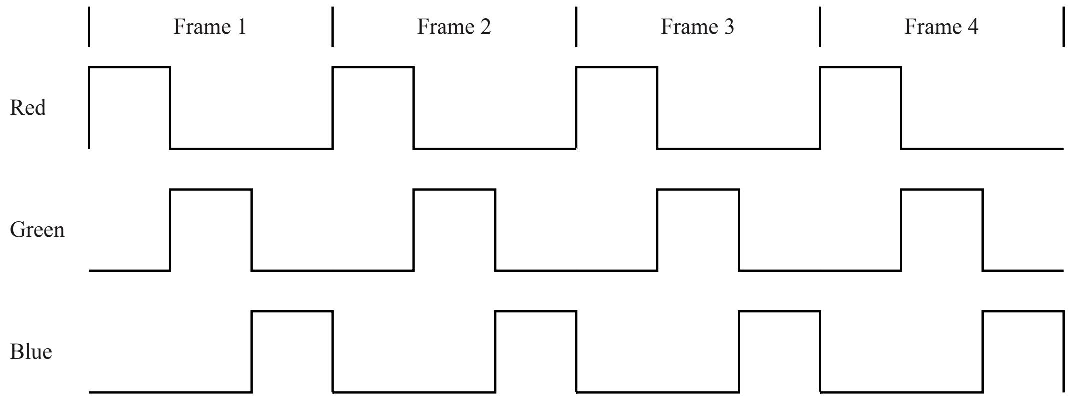


Fig. 3. The RGB timing diagram for a single scene generator shows three colors per image frame. In this diagram, "on" is high and "off" is low.

2.2. Image Generation

An ideal image generator would tile subimages in the pattern of Fig. 4. For a grayscale image, the subimage frequency can be calculated from the equation

$$f_{sub} = f_{frame} \times n_{sub} \times d_c \quad , \tag{2}$$

where f_{sub} is the subimage rate, f_{frame} is the frame rate, n_{sub} is the number of subimages/frame, and d_c is the color depth (1 for grayscale, 3 for RGB color). Since the 5 kpix × 4 kpix display under design tiles 20 subimages, a 60 Hz frame rate requires 1.2 kHz subimage rate for grayscale, 3.6 kHz for color.

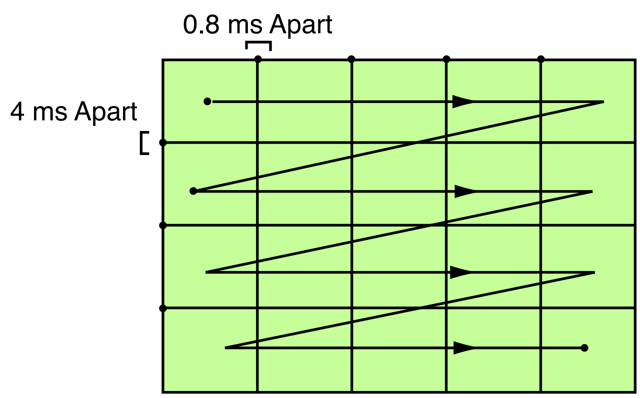


Fig. 4. A raster scan architecture for a 5×4 sub-image array.

The 60-Hz frame rate is chosen from the perceptual flicker frequency, the lowest frequency at which the eye integrates fully from one frame to the next. Under low illumination, this frequency is generally ~20 Hz, which is why motion pictures produce smooth apparent motion even with a 24-Hz frame rate. At brighter illumination the flicker frequency reaches 45 Hz, explaining why U.S. television operates at a 60-Hz field rate with two fields/frame. Thus, a 60-Hz image rate is significantly higher than the perceptual flicker frequency, even under bright illumination.

Recent research on scanned multibeam and multipanel displays[5], however, indicates that a 3.6-ms delay may cause unacceptable perceptual image distortions for time-varying imagery. In fact, the research indicates that any subimage rate <500 Hz could be detected as an image distortion. To avoid this, it is necessary to tile the subimage tiling displays (Fig. 5). Then adjacent subimages will appear at a rate of ~600 Hz, fast enough to avoid this distortion.

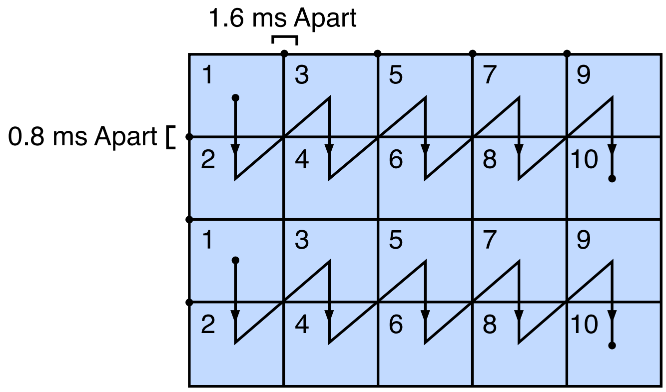


Fig. 5. By tiling two 5 × 2 subimage tilers, a 5 × 4 tiled display can ensure a subimage rate ≥600 Hz.

2.3. Display Characteristics

The display characteristics depend on the source of the image, whether it be live, the output of a sensor, or computer-generated. The resolution or addressability of the system can be measured or calculated as modulation transfer function (MTF), which is the product of the MTFs of the image source, the projection optics (including the image tiling scanner), and the projection screen (if any)[6,7]. The total display MTF is the product of these three subsystems:

$$MTF_{display} = MTF_{image\ source} \times MTF_{optics} \times MTF_{screen} \quad . \tag{3}$$

In this system, the component that requires the most careful attention is the projection optics, including the tiling system. The luminance or brightness (B_S) of the display also depends on the characteristics of the three components:

$$B_S = W_{source} \times \eta_{source} \times T_{system} \times \frac{G}{A} \quad , \tag{4}$$

where W_{source} = illumination power (watts), η_{source} = luminous efficiency of the illumination [30 lm/W at 450 nm (blue), 670 lm/W at 500 nm (green), and 65 lm/W at 650 nm (red)], T_{system} = system transmittance, G = screen gain, and A = viewing area or FOV. Since the designed display FOV, A, is small, low-power illumination will be bright enough for HMD applications.

The MTF of the projection optics is also affected by the quality of sub-image blending. For the image to be continuous and seamless, the separate projected scanned sub-images must match in terms of linearity, geometry, luminance uniformity, and color registration. Since the human eye is sensitive to discontinuities, simply edge butting sub-images together will introduce luminance nonlinearities, discontinuities at edges, and geometric convergence mismatch.

To overcome these deficiencies, the sub-images must be properly blended[8]. A standard approach of eliminating the luminance discontinuities in large wall displays can be adapted for use in HMDs, where the sub-image area is extended to overlap with gradual reduction in the luminance of the overlapping pixels. This approach can be easily applied using a scene projector with some extra pixels in both directions. For example, a 1024 × 1024 projector could have 24 pixels of overlap on each side and still have resolution of 1000 × 1000 pixels (Fig. 6). The luminance of these blending pixels can be adjusted electronically.

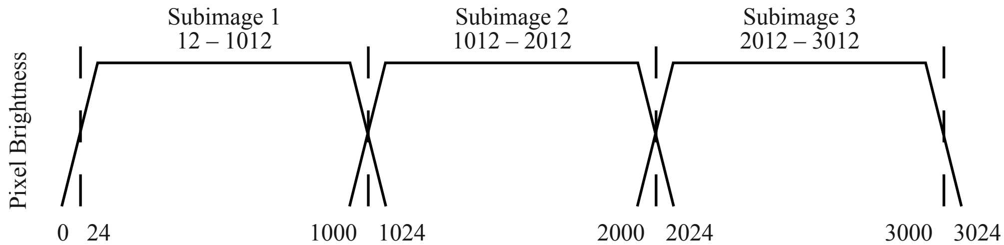


Fig. 6. Subimage edge pixels blend to form a smooth overall image.

3. DESIGN OF PROTOTYPE

To demonstrate the capability of subimage tiling to produce a good display, we designed a 4096 × 1024 pixel subscale prototype with a frame rate >60 Hz. The scene generator we selected was an analog liquid crystal on silicon (LCOS) spatial light modulator (SLM). This device had a resolution of 512 × 512 pixels and could generate ~1000 images/s. The analog SLM was chosen for its 7-8 bits of dynamic range without the need for pulse width modulation (PWM). Not only does the analog SLM have a greater dynamic range at the high subimage rates needed than a digital SLM (PWM rates limit the digital LCOS dynamic range to <6 bits), analog scene generation eliminates the image artifacts and flicker that are common in PWM displays. Using this SLM as a grayscale scene generator, Eq. (2) shows that 16 subimages can be tiled at a frame rate of 60 Hz by operating within the SLM capabilities, at 960 Hz. To avoid image distortion, the prototype was designed as an 8 × 2 array of 512 × 512 pixel subimages, with scan profile shown in Fig. 7.

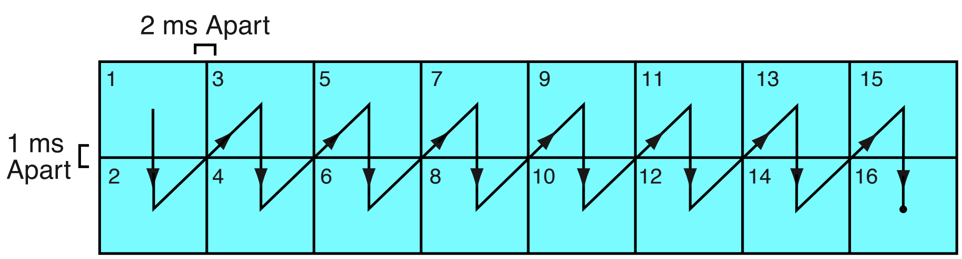


Fig. 7. By tiling vertically first, then horizontally, adjacent subimages appear at ~500 Hz, avoiding image motion distortion.

For this prototype, the subimages were just butted against each other. No effort was made to blend the edge pixels. The following requirements were established for the prototype:

- LCOS image rate: 16 subimages/frame × 60 frames/s = 960 Hz subimage rate
- Total prototype small enough for helmet mounting (5.2 × 5.6 × 1.8 in.)
- Prototype laser source green, 532 nm, 200 mW (can be reduced by ND filters)
- Output luminance 1.4 cd/cm^2 peak (bright enough for use in full sunlight) with 200 mW illumination (corresponds to 350 cd/m^2 with 5 mW illumination)
- Total optical throughput ~1%
- Display screen: 20° FOV, resulting in gain of ~18

4. EXPERIMENTAL RESULTS

The HMD prototype was tested in the laboratory. In addition to viewing its output by eye (Fig. 8), we tested the display for its quality in uniformity, contrast, dynamic range, flicker, image noise/speckle, and optical throughput. The results appear in this section.

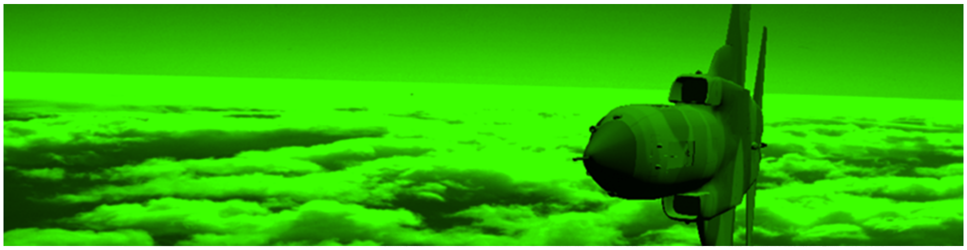


Fig. 8. Typical image used to test the tiling display.

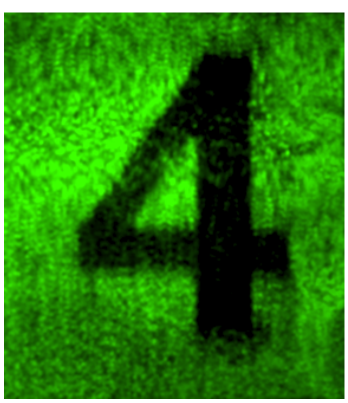
4.1. Image Uniformity

The uniformity of the image is critical for a display. For the prototype uniformity test we projected a simple, repeating pattern (Fig. 9) to show where bright and dim spots occurred. The preliminary tests indicated that the major uniformity challenge was not within the SLM—we could achieve a uniformity figure of ±0.5%—but between adjacent subimages. This was caused by slight misalignments of the tiling elements, leading to slight rotation of subimages. These minor misalignments also caused some of the subimages to be darker on one side than on the other. Careful realignment of the tiling elements resulted in significant uniformity enhancement (Fig. 1). If tile-to-tile uniformity is a challenge in the final display, electronic brightness corrections can be made for each subimage using a look-up table in the SLM driver software.

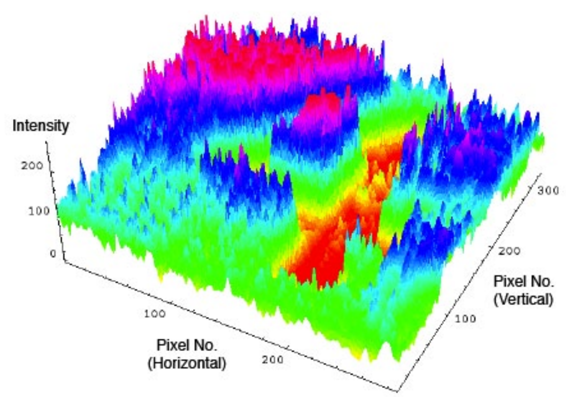
Fig. 9. Tiled image used for uniformity testing. Edge pixels are not blended.

4.2. Display Contrast

The display contrast was tested using the image shown in Fig. 1. The subimage including the number “4” was selected for this measurement. This is shown, together with its intensity profile, in Fig. 10. With the SLM contrast set to ensure full brightness on the “4” pattern, the minimum brightness in that subimage is 0. This corresponds to a maximum contrast value of 100%. Noise in the image reduces the effective contrast to 99.6%.



(a)



(b)

Fig. 10. Image (a) and intensity pattern (b) used for measurements of contrast, noise, and dynamic range.

4.3. Dynamic Range

As shown in Section 4.2, a typical subimage has minimum intensity of 0. An examination of Fig. 10(b) shows that each level is accessible, although the brightness at the edges of the subimage is ~40% lower than in the center. The actual number of levels is thus ~155, defining a dynamic range of 7.2 bits.

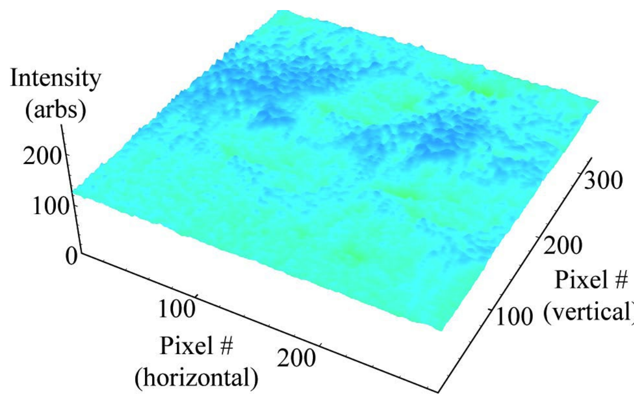
4.4. Scene Rate/Flicker

There is no noticeable flicker on the display. The subimage rate is set by the SLM to 1016 Hz. The full frame rate is 1/16 of the scene rate, or 63.5 Hz. This is greater than the maximum flicker frequency of the eye, so no flicker is expected. In addition, the maximum time delay between adjacent subimages is 1.97 ms, short enough to avoid image degradation.

4.5. Image Noise

Image noise is the difference between an actual image (Fig. 10(a)) and a perfect representation of that image. The difference between the brightness and a perfect image is shown in Fig. 11. A statistical analysis demonstrates that the RMS noise in this image is 0.435 arbitrary units (out of 255), or 0.170%. Examination of Fig. 10(a) indicates that most of this is speckle from the laser illumination, which can be eliminated by using an incoherent illumination source, such as a LED.

(a)



(b)

Fig. 11. Image (a) and intensity profile (b) of the image noise.

4.6. Optical Throughput

The throughput of the display is listed in Table 1. With a 200-mW unpolarized laser source operating at 532 nm, the final output brightness is 14,000 cd/m^2 peak. This is significantly brighter than a typical computer display, and approximately the same as that of current HMDs designed for use in full sunlight. The luminous efficiency as a function of wavelength[7] indicates that an equivalent power of blue light would result in 400 cd/m^2, while the same red light would produce luminance of 650 cd/m^2.

Table 1. Optical Throughput of the HMD Prototype.

Section	***Throughput***
Input Optics	92%
Polarizer	47%
Input Section	**43%**
SLM (optimized for red)	24%
Projection Optics	92%
Projection Section	**22%**
Beam Size Mismatch	24%
Each Optical Stage	84%
Tiling Section (total)	**10%**
Throughput (total)	***0.95%***

The major sources of loss include the polarizer (the incoming beam is unpolarized but the tiled beam is linearly polarized), the SLM (which has a maximum efficiency of 45% and is optimized for the red, although we are illuminating with green), and the mismatch in size between the projected beam and the tiling optics. These can all be improved, resulting in a projected throughput of >10%. At that throughput level, even 10 mW of green illumination will be too bright, although the red and blue illumination will need more power than this.

5. SUMMARY AND CONCLUSIONS

POC has developed a new image tiling HMD prototype that can produce superhigh resolution, photorealistic images without the limitations of non-tiled images (exceptionally high data rate for large LCD images and beam spreading/defocus for MEMS scene generators). Future versions will include an eye-limited, full-color HMD, which will require ~5 kpix × 4 kpix resolution on a screen positioned such that a single pixel subtends ~1 arc-min. The current subscale prototype operates in the green (monochrome) and has a total resolution of 4 Mpix (4k × 1k). This is based on currently available analog SLMs with resolution of 0.5 kpix × 0.5 kpix and image rate of 1 kHz. This array of 8 × 2 subimages is a prototype for a 5 kpix × 4 kpix display formed by tiling together two subdisplays, each of which is itself a 5 × 2 array of 1 kpix × 1 kpix subimages with an image rate >1 kHz. LCOS SLMs with this resolution and image rate are predicted by their manufacturer to be available in two to three years.

6. ACKNOWLEDGEMENTS

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REFERENCES

1. P.G.J. Barten, *Contrast Sensitivity of the Human Eye and Its Effects on Image Quality*, SPIE Press, Bellingham, Washington, 1999.
2. F.J. Ferrin, "Current Issues in Helmet-Mounted Display Systems for Military Applications," *Helmet- and Head-Mounted Displays III*, *Proc. SPIE,* vol. 3362, 71-79, 1998.
3. T.M. Lippert, C.E. Rash, and J.J. Hauser, "Microvision, Inc. And U.S. Army Aviation Develop Laser Scanning HMD," *Helmet- and Head-Mounted Displays V*, *Proc. SPIE,* vol. 4021, 58-65, Orlando, Florida, 2000.
4. M. Hereld, I.R. Judson, and R.L. Stevens, "Introduction to Building Projection-Based Tiled Display Systems," *IEEE Comput. Graph. Appl.*, **20**, 22-28, 2000.
5. J.M. Lindholm, "Multibeam and Multipanel Displays: Some Perceptual Effects of Scan Architecture," *J. SID*, **9**, 125, 2001.
6. M.A. Karim, ed. *Electro-Optical Displays*, Marcel Dekker, Inc., New York, 1992.
7. D. Malacara, *Color Vision and Colorimetry: Theory and Applications*, SPIE Press, Bellingham, Washington, 2002.
8. K. Li, H. Chen, Y. Chen, D.W. Clark, P. Cook, S. Damianakis, G. Essl, A. Finkelstein, T. Funkhouser, T. Housel, A. Klein, Z. Liu, E. Praun, J.P. Singh, B. Shedd, J. Pal, G. Tzanetakis, and J. Zheng, "Building and Using a Scalable Display Wall System," *IEEE Comput. Graph. Appl.*, **20**, 29-37, 2000.