Helmet- and Head-Mounted Displays and Symbology Design Requirements II

PROCEEDINGS

SPIE—The International Society for Optical Engineering

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Ronald J. Lewandowski
Wendell Stephens
Loran A. Haworth
Chairs/Editors

18–19 April 1995
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Introduction

SPIE's Helmet- and Head-Mounted Displays and Symbology Design Requirements II conference had a record number of attendees. Interest continues to grow in head-mounted displays and related technologies.

The 1995 conference included a wide variety of papers related to new display technologies, head tracker technologies, flight safety, HMD symbology, and HMD testing. Session 1 of the conference presented HMD technology and hardware for both military and commercial use. Miniature flat-panel image sources being developed under ARPA funding continue to dominate funded programs. In the past two years, more than a dozen dual-use programs have been initiated.

While advances in technology and hardware are bringing us closer to further production applications, the issues related to operational use of head-mounted systems are gaining attention. Session 2 addressed flight testing and evaluation, and Session 3 covered head-mounted display human factors studies and testing issues which are key to the operational use of HMDs. Session 4 rounded out the conference with symbology development and evaluation.

I join my cochairs, Wendell Stephens and Loran Haworth, in thanking the session chairs, Chris Bartlett, Henry Girolamo, Gary Kessler, and Robert Osgood who, along with the authors, made this conference possible.

Ron Lewandowski

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SESSION 1

Hardware Development and Evaluation

Development of a commercial retinal scanning display

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ABSTRACT

The Human Interface Technology Laboratory at the University of Washington is developing a new display device, the Virtual Retinal Display (VRD), in which a coherent light source is used to scan an image directly on the retina of the viewer's eye. Development work is funded by Micro Vision, Inc., Seattle, which holds an exclusive license to manufacture and distribute the VRD. Using the VRD technology it is possible to build a high resolution, wide field-of-view, full color personal display device that is light weight and will operate in a high brightness environment. Current work is aimed at developing the technologies that will make the VRD a commercially viable product from both a performance and cost standpoint. Prototypes produced to date include a full color, VGA resolution device based on a unique mechanical resonant scanner as the horizontal scanning element. This paper will briefly explain the VRD concept and discuss potential applications of the technology. It will also describe the current research and development efforts which are aimed at creating a high performance yet low cost display system.

1. INTRODUCTION

The Human Interface Technology Laboratory (HITL) at the University of Washington, in partnership with Micro Vision, Inc., is developing the Virtual Retinal Display (VRD) [1,2], a novel display device that does not require the use of a cathode ray tube or flat panel display screen. Instead, a coherent light source is utilized to scan an image on the retina of the viewer's eye. The VRD approach has several advantages:

- The display's resolution is limited by diffraction and optical aberrations in the scanned beam and not by how small an individual pixel element in a large array of pixel elements can be made. It can therefore display very high resolution images.
- The display's brightness is controlled by the brightness of the scanned beam. With a laser as the light source the display is bright enough for use outdoors, on a bright day.
- The display can operate in either an inclusive or a see-through mode. The see-through mode is generally a more difficult system to build as most displays are not bright enough to work in this mode when used in a medium to high illumination environment.
- The display requires only simple and well understood manufacturing processes and thus can be low cost.

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- The display projects most of its generated light into the eye and can thus be very energy efficient, resulting in low power consumption.

- All components in the VRD are small and light, ideally suited to a portable display.

To create an image with the VRD a photon source (or three sources in the case of a color display) is used to generate a beam of light. The use of a coherent source (such as a laser diode) allows the system to draw a diffraction limited spot on the retina. The light beam is intensity modulated to match the intensity of the image being rendered. The modulation can be accomplished after the beam is generated. If the source has enough modulation bandwidth, as in the case of a laser diode, the source can be modulated directly.

The resulting modulated beam is then scanned to place each image point, or pixel, at the proper position on the retina. Our development focuses on the raster method of image scanning and allows the VRD to be driven by standard video sources. To draw the raster, a horizontal scanner moves the beam to draw a row of pixels. The vertical scanner then moves the beam to the next line where another row of pixels is drawn.

After scanning, the optical beam must be properly projected onto the retina. The goal is for the exit pupil of the VRD to be coplanar with the entrance pupil of the eye. The lens and cornea of the eye will then focus the moving beam on the retina, forming an image. A simple block diagram of the VRD is shown in Figure 1.

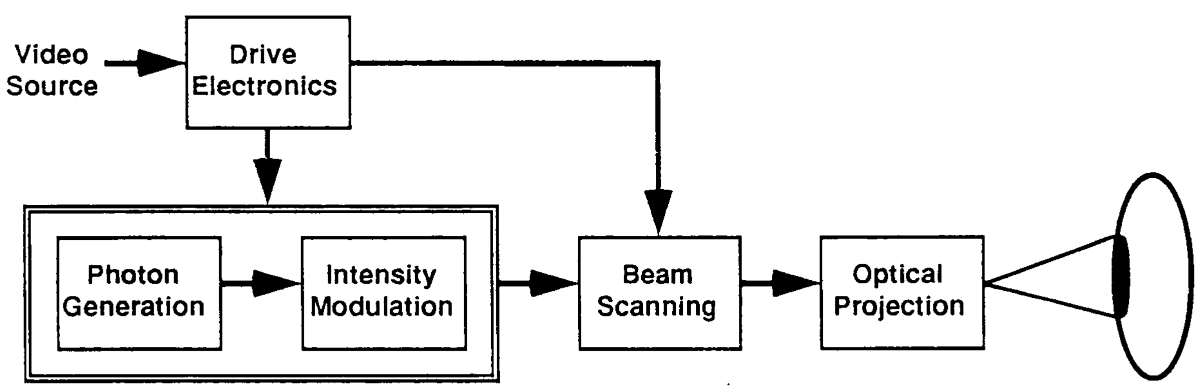


Figure 1 - Virtual Retinal Display Block Diagram

The process of scanning a coherent light source on the retina was used by Webb [3,4] in the development of the scanning laser ophthalmoscope. In Webb's system the portion of the optical beam that reflected off the retina and passed back through the lens and cornea of the eye was captured. The captured signal was then used to modulate a synchronized video signal allowing an image of the retina to be displayed on a CRT. Webb noted that if the input optical beam were modulated, the patient perceived an image.

Many of the issues that need to be considered for a commercial display device were not addressed by Webb because they were not as important for a special purpose medical instrumentation system. These issues include cost, size, portability, high resolution, and color It is the goal of our current work to develop the technologies that will allow commercially viable products to be produced based on the retinal scanning concept. Specifically, our development targets are as follows:

- System manufacturing cost should be less than $100 for a monocular display and $200 for a stereo display in large quantities.
- A head mounted stereo display should weight less than 8 ounces.
- Systems should be capable of resolutions of 1024 lines at a 60 Hertz frame refresh rate.
- Full color and monochrome systems should be available.
- Systems should be bright enough to allow see-through operation outdoors.

2. HORIZONTAL SCANNING

A key issue in developing a cost effective and portable VRD is developing a method of scanning the optical beam in the horizontal direction. The ideal horizontal scanner would scan a large diameter optical beam over a wide scan angle at a high scan frequency. In addition, the scanner would not introduce optical or chromatic aberrations. Specific requirements of the horizontal scanner are discussed below.

To be compatible with existing video standards it is desired that the VRD scan in traditional raster formats. The scan rates for these formats can be determined by multiplying the number of lines in the display by the refresh rate of the display. On the low end is the RS-170 standard for interlaced video which contains 525 lines that are refreshed 30 times per second resulting in a horizontal scanning frequency of 15,750 Hertz. A typical high resolution computer monitor contains 1024 lines that are refreshed 72 times a second, for a horizontal scan rate of 73,728 Hertz.

The field-of-view or image size seen by the user is directly related to the angle through which the optical beam is scanned. The scan angle for the faster horizontal scan is not likely to match the total angular field-of-view desired for the display. An optical system must therefore be used to magnify the scan angle. Unfortunately, because of the optical invariant, as the scan angle is optically increased the optical beam diameter is decreased. This effect can be characterized by the equation

$$D(in) * \tan(\phi(in)) = D(out) * \tan(\phi(out))$$

where

$D(in)$ = diameter of the input optical beam (or it's limiting aperture)

$\phi(in)$ = half angle of the input optical beam's deflection

$D(out)$ = diameter of the output optical beam (the exit pupil)

$\phi(out)$ = half angle of the output optical beam's deflection.

Angular resolution of the display is limited by aberrations in the optical system and by diffraction. The diffraction limiting aperture in a practical VRD is the system's exit pupil which, in most practical designs, is the projection of the aperture of the horizontal scanning device. Using Rayleigh's criteria for resolving two points, angular resolution can be computed as

$$\theta = 1.22\,\lambda / D(out)$$

where

θ = angular resolution

λ = wavelength of light

D(out) = diameter of the circular exit pupil.

Substituting we find that

$$\theta = 1.22\,\lambda * D(in) * Tan(\phi(in)) / Tan(\phi(out))$$

where in a VRD

D(in) = aperture of the horizontal scanner

ϕ(in) = half angle of the horizontal scanner's deflection

ϕ(out) = half angle of the system field-of-view.

Thus, for best resolution we desire the widest possible scanning aperture and the largest possible scanner deflection.

In addition, a small exit pupil necessitates exact eye alignment for an image to be seen. A head mounted system with too small an exit pupil will not allow wearers to move their eyes to view details at the edges of the image.

Two basic classes of scanners were analyzed for the VRD application. The first group operate on the principle of diffraction through a variable grating. These scanners include both electro-optic (primarily experimental) and acousto-optic (commercially available) devices. A typical acousto-optic scanner can operate at a high scan frequency but has a small scan angle. One representative device (manufactured by Brimrose, Inc.) has a 13.6 mm aperture and a half angle of scan of approximately 1.75 degrees. A VRD constructed using this device with a 50 degree field-of-view would have a .9 mm exit pupil and an angular resolution of 3 arc minutes.

While it is possible to build a working retinal scanning display with an acousto-optic scanner, it is difficult to built a commercial product based on this technology. First, to achieve good resolution, the scanner requires optics to shape the input beam for deflection and additional optics to reform the output beam to the desired shape. This leads to a system that is much larger than desired and one in which multiple optical surfaces must be precisely aligned. Second, the drive frequencies needed for the scanner are in the 1 to 2 gigaHertz range. The drive electronics and cabling for a system operating at these frequencies adds considerable cost and complexity to the product. Third, the acousto-optic scanner will deflect light of different wavelengths at different angles. This can be corrected for in the electronics but would add considerable cost and size to the system. Finally, the devices are expensive and will not, in the foreseeable future, allow for a cost effective display.

The second class of scanners operate by reflecting the optical beam off a mirrored surface which is moving such that the beam's angle of incidence relative to the surface is changing. Devices in this category include piezoelectric deflectors, galvanometers, rotating polygons, and resonant scanners. Piezeo electric deflectors have very small deflection angles (<1 degree) which would require significant magnification to obtain a usable field-of-view. As discussed above this leads to a very small exit pupil and low resolution. Galvanometers are capable of scanning through wide angles (>60 degrees) with a large aperture but at frequencies that are much lower than desired for the horizontal scan. These devices will work well for the slower vertical scan operating at 60 to 100 Hertz. Rotating polygons are capable of performing the horizontal scan;

however the rotational velocity required and the mechanical inertia generated [5] make this method unsuitable for a hand held or head mounted display. Resonant scanners appear to offer the best solution but the current generation of commercially available resonant scanners do not operate at the desired frequencies. Typical devices operate up to approximately 8 kHz.

To meet the horizontal scanning requirements HITL engineers have developed a mechanical resonant scanner (patent applied for) with many unique features. Foremost among these is the fact that the device has neither a moving magnet nor a moving coil. Instead, it uses a flux circuit whose only moving part is the torsional spring/mirror combination. Eliminating moving coils or magnets greatly lowers the rotational inertia of the device, thus raising the potential operating frequency. Devices have been built that will support over 800 display lines at a 60 Hertz refresh rate. Figure 2 shows the mechanical resonant scanner.

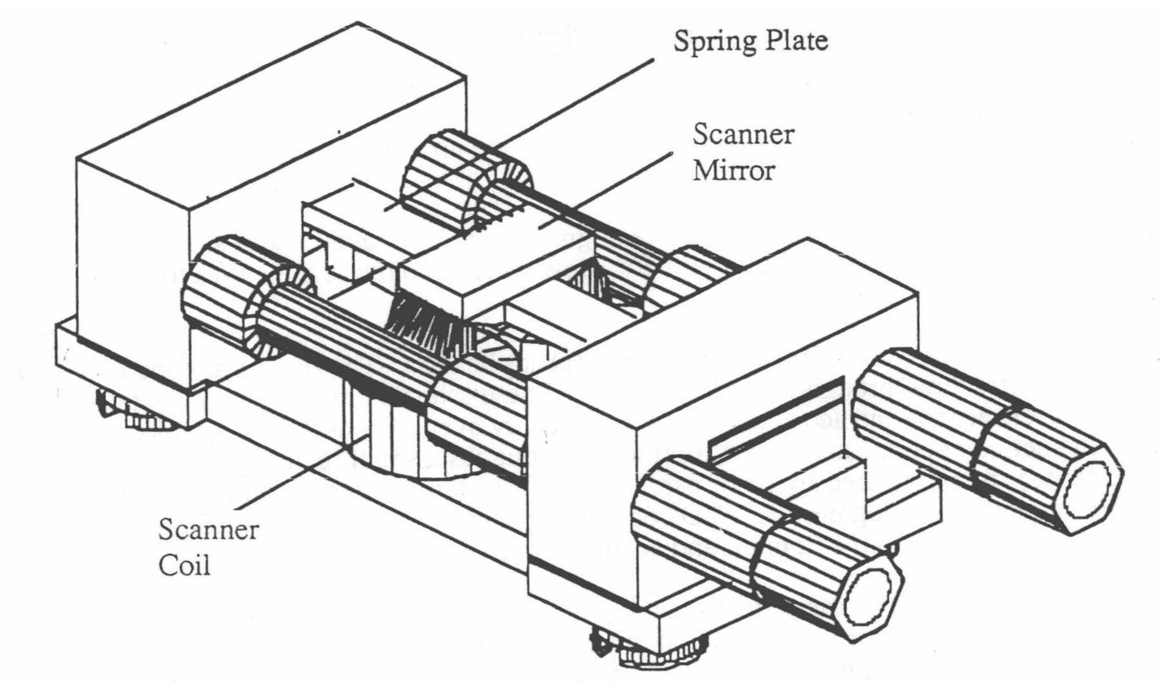
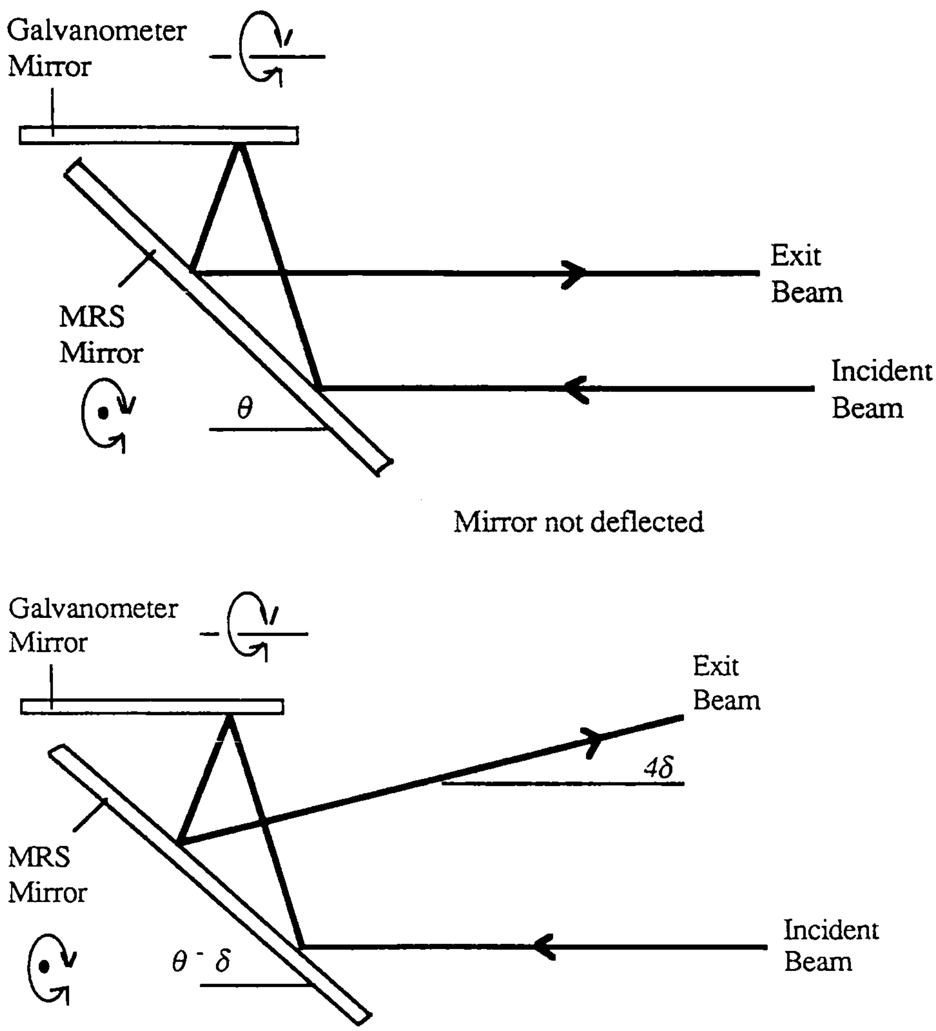


Figure 2 - Mechanical resonant scanner

The majority of our recent work has centered around developing and perfecting the mechanical resonant scanner for use in a 640 by 525 line, 60 Hertz VGA display. This device has a mirror size of 3 mm by 6 mm. The mechanical deflection, when driven at resonance, is 8 degrees. This results in an optical beam deflection of 16 degrees. The mechanical resonant scanner can be used in conjunction.with a second mirror (this mirror could be stationary or, as is the case with our prototype systems, the vertical scanning mirror) which allows for an increase in the optical scan angle. The two mirrors are arranged such that an optical beam undergoes multiple reflections off the scanning mirror. When this occurs the optical scan is multiplied by the number of reflections off the scanning mirror, see Figure 3. Optical scan multiplication factors of 2X and 3X (4X has been achieved with smaller mechanical deflection) have been realized resulting in total scan angles of 32 and 48 degrees.



Mirror deflected through the angle δ

Figure 3 - Scan angle multiplication [6]

In addition to the large scan angle and high scanning frequency the mechanical resonant scanner exhibits several other features that make it ideal for use in a commercial VRD. The device is small, measuring .9 centimeters high by 1.3 centimeters wide by 2.8 centimeters long. The drive signal is a low (±15 volts) voltage sinusoidal or square wave at the resonant frequency. The system has a large amount of stored energy resulting in a very uniform and repeatable scan. Being a reflective device, all colors are reflected at the same angle. Finally, the mechanical resonant scanner is made from common materials and requires no exotic manufacturing processes resulting in a volume manufacturing cost estimated to be under $3.

3. CURRENT PROTOTYPE

A bench mounted prototype, using the mechanical resonant scanner as the horizontal beam scanner, has been developed. The prototype delivers VGA resolution images in full color or monochrome. Performance specifications for this system are shown in Table 1.

Parameter	Specification
Horizontal resolution	640 points
Vertical resolution	525 lines total 480 lines visible
Refresh rate	60 Hertz non interlaced
Field-of-view	40 degrees, see-through mode 50 degrees, inclusive mode
Color	Monochrome, red only or Full color (R, G, B)

Table 1 - VRD prototype specifications

In the prototype the mechanical resonant scanner is packaged with a galvanometer (used for vertical scanning) in a small scanning engine. The optical path is configured such that the optical beam reflects off a relay mirror onto the horizontal scanner. From here the beam reflects off the vertical scanner and back off the horizontal scanner before exiting the scanning engine through a window. With this configuration the horizontal scan angle is doubled as described above with a scan angle of 25 degrees obtained.

In the monochrome mode, the prototype uses a single directly modulated red laser diode. Two lenses are placed after the laser to produce the desired beam. The first is a cylindrical lens that produces equal divergence in both laser axes. The second produces a slightly converging beam. The lenses are mounted with the laser and this unit is plugged directly into the scanning engine. The beam deflects off the scanners and comes to focus at a point outside the scanning engine. The focus plane is positioned at the focal point of an eyepiece. Proper choice of the eyepiece focal length will then produce the desired system field-of-view.

In the color mode, the prototype uses three light sources, a directly modulated red laser diode and externally modulated green and blue gas lasers (helium neon for green and argon for blue). The colors are combined using dichroic beamsplitters producing a single color beam. Blue and green intensity modulation is achieved using two acousto-optic modulators. One problem encountered in this arrangement is the different phase delay between the blue and green signals and the red signal. A delay is introduced in the blue and green signals through the acousto-optic modulator. This delay corresponds to the time it takes the acoustic wave to travel across the crystal to the point where the laser beam is encountered. Adjusting this for the minimum distance yielded a delay of approximately 100 nanoseconds. To compensate for this a delay line was placed in the red signal path.