Scanned Laser Displays for Head Mounted Displays

Douglas E. Holmgren
Department of Physics and Astronomy

Warren Robinett
Department of Computer Science
University of North Carolina, Chapel Hill, NC

Abstract

Technologies applicable toward a display system in which a laser is raster scanned on the viewer's retina are reviewed. The properties of laser beam propagation and the inherent resolution of a laser scanning system are discussed. Scanning techniques employing rotating mirrors, galvonometer scanners, acousto-optic deflectors, and piezo-electric deflectors are described. Resolution, speed, deflection range, and physical size are strongly coupled properties of these technologies. For head-mounted display applications, a monochromatic system employing a laser diode source with acousto-optic and galvonometer scanners is deemed most practical. A resolution of 1000 x 1000 pixels at 60 frames per second should be possible with such a sytem. A radiometric analysis indicates that eye safety would not be a problem in a retina-scanning system.

Introduction

The recent interest in incorporating display devices into Head-Mounted displays (HMDs) imposes new requirements on display devices, particularly in terms of resolution, weight and volume. While small CRT and LCD displays exist, a 1-inch, 1000-line color CRT or LCD display is not currently available. Poor resolution is currently one of the major technical problems of HMDs, and this provides incentive to consider alternative display technologies that may be superior to CRTs and LCDs for use in HMDs.

The Private Eye[1] has demonstrated that a small, lightweight, medium-resolution monochromatic display can be built by modulating the elements of a 1-dimensional LED array and using a moving mirror to sweep out a 2D virtual image. The Private Eye's LED array has 280 elements which are swept to form a 720 x 280 resolution image. The resolution of this display device could be improved by using more elements in the LED array and modulating faster, but getting color is problematic because blue LED arrays would be needed, and single discrete blue LEDs have only recently become available.

Ordinary displays such as CRTs and LCDs form an image on a 2D array of display elements. The Private eye performs a 1-dimensional sweep of a 1D array of display elements to form a 2D image. A third possiblity is to sweep a single rapidly modulated display element through a 2D raster pattern to form a 2D image. Such a system would most likely use a laser (or LED) as the display element, since these devices can be modulated at the required rates. Displays of this last type are the topic of this study.

We surveyed laser-based display technologies to determine if any might be applicable to a head-mounted display. We were primarily interested in a retina scanning system, in which the desired scene is directly drawn on the user's retina without an external display screen.

Figure 1 shows an optical schematic for a "Direct Retina Write" (DRW) display. Light from the laser is first intensity modulated by the modulation device M. It is then deflected in the

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[1] Roger S. Reiss, "Instrument Design," OE Reports April 1990, p.13.

horizontal plane by beam deflector H. The lens pair R1 relays the deflected beam to the second deflection device V which imparts a deflection in the vertical plane (orthogonal to the plane of Figure 1). The lens pair R2 relays the deflected beam to the user's pupil. The optics are arranged so that the beam arriving at the pupil is collimated; therefore the eye focuses the beam to a tiny spot on the retina. The beam is continuously scanned in a raster pattern, forming a "flying spot" image on the retina. This scanning system is similar to that employed in scanning laser ophthalmoscopes.[2]

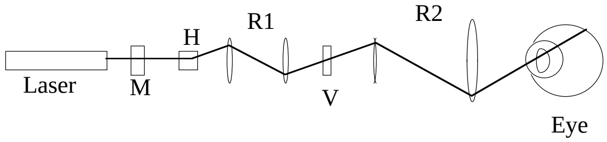

Figure 1

A Direct Retina Write (DRW) display system would clearly be a novel display technique. It would effectively remove the many layers of transmission media that exist between scene and visual sensation, and allow a direct (light) path between information and vision. In our study we were interested in determining whether a DRW display might eventually make a viable display technology. We considered standard display specifications of resolution, field-of-view, frame rate, grey-scale, and color. In addition we wanted to know whether a DRW system might be developed for use in a small, lightweight HMD.

This report surveys the current laser scanning technologies which could be incorporated today into making a laser display. We considered four specific methods: 1) rotating polygon mirrors, 2) galvonometer mirror scanners, 3) piezo-electric mirror deflection, and 4) acousto-optic deflectors. (A fifth scanning technique using electro-optic deflection was dropped from consideration because of the poor resolution obtainable.)

Our general conclusion is that none of these technologies promised a display system that would be clearly superior to current CRT and LCD displays in HMD applications. It was determined that the best DRW system feasible with current off-the-shelf technology would use a small laser diode and incorporate a monochromatic (red) high resolution (1000x1000) raster scan laser display using acousto-optic deflection for fast "horizontal" line scans and slower galvonometer deflection for the "vertical" direction, with 60 frames per second possible. Intensity modulation up to 60 MHz could be accomplished by directly modulating the laser diode drive current. Magnifying optics would be required to obtain fields-of-view greater than 3°. The system would probably be similar in size and weight to CRT- or LCD-based HMDs currently in use. A color DRW display will be possible in the next 3 to 5 years, when blue laser diodes are expected to become available.

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[2] R. H. Webb, G. W. Hughes, and F. C. Delori, "Confocal scanning laser ophthalmoscope," Applied Optics 26, pp. 1492-1499 (1987).

Laser Displays

Lasers have three properties that distinguish them from more ordinary light sources (e.g. LEDs, CRT fluorescence, incandescent lamps).

- Laser light is highly monochromatic.
- Laser light is generally highly collimated or beam-like which allows one to focus it to the smallest spot size allowed by diffraction.
- Laser light is generally very intense.

When we contemplate making a display system using a laser, it is useful to consider which properties of the laser radiation are important to the display function. For instance, we might consider making a large-screen TV using lasers scanned in a raster pattern on a display screen, much like an electron beam is scanned on the phosphor screen inside a CRT. In this application, the beam-like character of the laser light and its high intensity are very useful characteristics that would enable us to make a display with adequate brightness. The monochromatic character of the laser would be important only if the laser deflection method required it, as for example in acousto-optical and electro-optical deflection methods.

A direct retinal write display system, which motivates this study, most likely would not be dependent on the laser's high intensity. In fact, the retina's sensitivity would require that the laser intensity be attenuated many-fold to prevent eye injury or discomfort. Because of the scanning nature of this kind of display, like in the large-screen TV example, the laser's collimated beam is useful, but not mandatory, for scanning high resolution (small spot) pictures on the retina. The primary reason why one would choose to use a laser rather than an incoherent source in a direct retinal write display is because such a display system, particularly if head-mounted, would likely use acousto-optic deflection methods, which work well only with monochromatic light.

For head-mounted displays we require small and lightweight components. Laser diodes are ideal for this. They are small, inexpensive ($100s) and extremely efficient , require low voltage (< 3 volts) and are easily modulated. However, at present only deep red (>655 nm) laser diodes are available in the visible spectrum. Devices that operate at green and blue wavelengths are still in the research and development stage[3] but are projected to be available in 3 to 5 years.[4] For the present, we have to be content with monochrome displays based on laser diodes.

For benchtop prototypes and vision research applications, alternatives to using laser diodes for retina scanning are the common gas lasers. Helium neon lasers are relatively inexpensive and easy to use, and are available in red (633 nm) and green (543 nm) wavelengths. Argon lasers are capable of producing blue and green wavelengths, but are more expensive ($1000s) and inefficient (require water or forced-air cooling). Any of these gas lasers (particularly the argon laser) are too large for head-mounting. One can use optical fiber to pipe the light from a bench-top table laser to a head-mounted apparatus.

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[3] M. A. Haase, J. Qiu, J. M. DePuydt, and H. Cheng, "Blue-green laser diodes," Appl. Phys. Lett. 59, pp. 1272-1274 (1991).

[4] P. Zory, "Diode lasers lead in visible/IR performance," Laser Focus 27, pp. 89-102 (1991).

Properties of Laser Beams

In order to understand the capabilities and limitations of a laser-based display, it is helpful to review the propagation properties of a laser beam.

The most striking characteristic of the beam produced by a laser is its well-defined pencil- or beam-like nature. The laser output is inherently diffraction limited, which means that its tendency to spread-out as it propagates is minimized to the extent allowed by Maxwell's equations. Nonetheless, any laser beam diffracts and eventually spreads in transverse extent, and this tendency puts a fundamental limit on the resolution of a laser based display.

The simplest laser beam to describe in a mathematical sense is called a gaussian beam.[5] The beam produced by the common laboratory helium-neon (HeNe) laser is an example of a gaussian beam. We will denote the axis down which the laser beam propagates as the z axis. The cross-section intensity distribution of a HeNe laser beam is the gaussian function shown in Figure 2, falling off in intensity from the beam axis as $\exp[-(r/w)^2]$, where w is the so-called "spot size" of the beam at the particular beam location of interest and r is the distance from the beam propagation or z axis. Roughly speaking, we say a laser beam has a radius or spot size w at some particular point along the propagation axis.

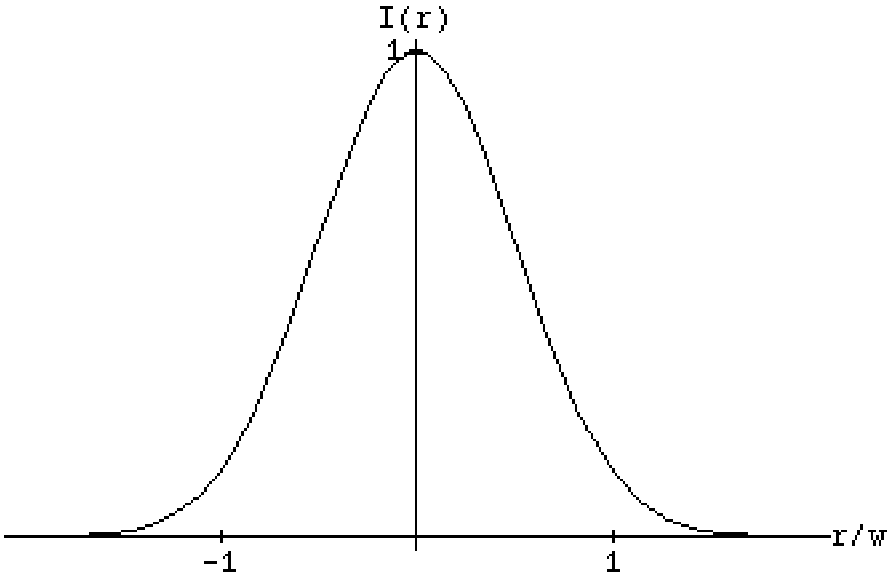

FIGURE 2

A laser beam will have some location along z, known as the "waist" where w has its minimum value, w_o. For an ordinary HeNe laser, the waist is generally located at the emitting aperture of the laser, or very close (within tens of centimeters) to this aperture. Because of diffraction, the laser beam spot size w increases as the beam propagates away from the waist location. The smaller the waist spot size, the more quickly the spot size increases with distance from the waist. Eventually the increase of w with distance becomes constant, allowing one to define a beam diffraction angle θ, as shown in Figure 3. A well known result from diffraction

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[5] For a complete treatment of Gaussian beam theory, see Ch. 13 of Lasers by A.E.Siegman.

theory states that the diffraction angle θ is given by the ratio of laser wavelength λ to the waist size w_o (to within a constant factor of order unity).

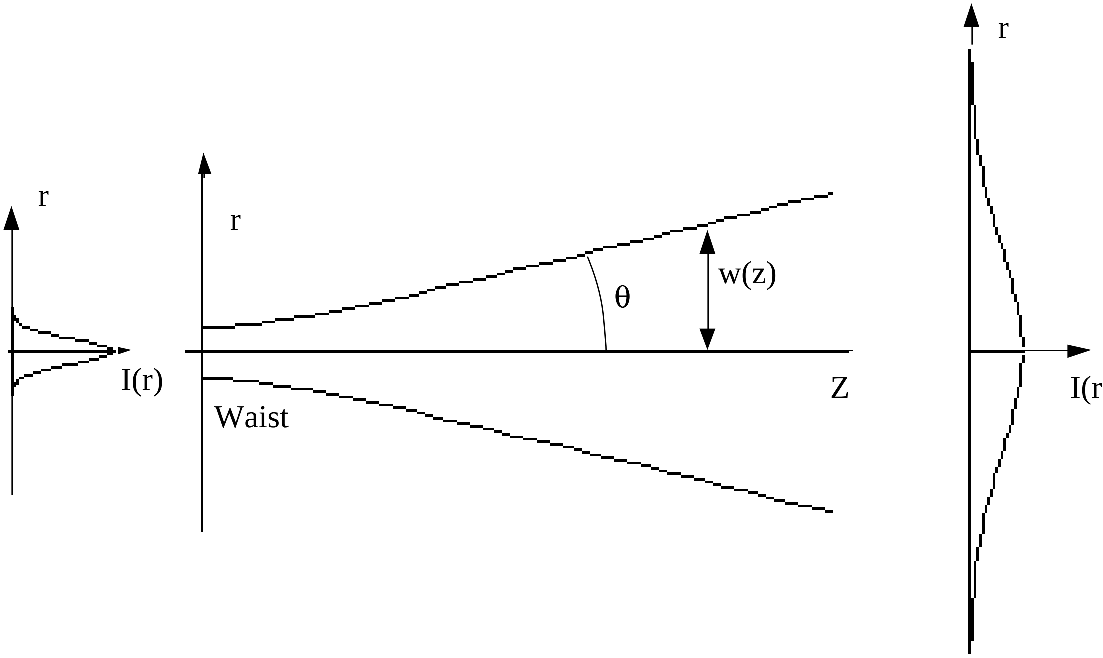


FIGURE 3

A very useful parameter for characterizing a laser beam is the collimated range,. This is a length along a laser beam, centered at the waist, within which the spot size w is less than $\sqrt{2}$ times the waist size w_o. The smaller the waist size w_o, the smaller the collimated range. The table below gives some representative values for the HeNe laser wavelength of 633 nm.

w_o	Collimated range	Diffraction θ
2.25 mm	50 m	1.8 x 10^{-4} radians
1.0 mm	10 m	4 x 10^{-4}
0.32 mm	1 m	1.3 x 10^{-3}
23 μ	5 mm	1.8 x 10^{-2} (≈1°)

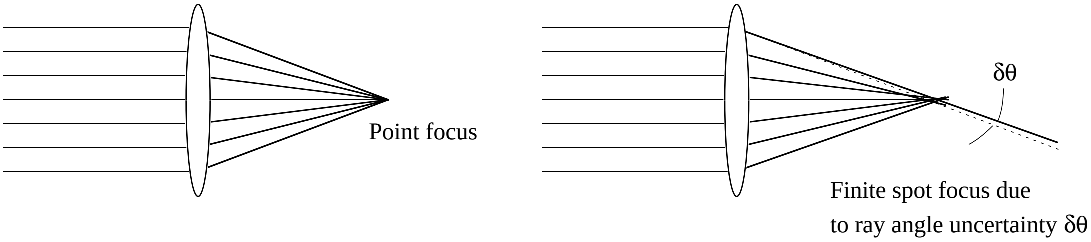
Thus there is a trade-off between the "narrowness "of the beam (w_o), and the distance along which it will remain narrow (collimated range).

Using optical elements such as lenses, we can produce additional waists in a laser beam; in essence one uses a lens to focus the beam to a waist whose location and size are determined by the lens focal length and the spot size of the beam incident on the lens.

The foregoing has applied to the ideal gaussian beams produced by most gas lasers. The beam character of radiation from laser diodes differs enough from a simple gaussian to deserve additional comment. Laser diodes produce light within a very small waveguide/pn-junction structure, whose transverse dimensions are typically a micron or so in the direction perpendicular to the junction and a few microns and up in the direction parallel to the junction. Since these dimensions are close to the wavelength of light emited, diffraction effects are very pronounced. The beam diverges very rapidly as it emerges from the diode. One can "capture" this diverging beam with a good collimating lens or a suitably designed GRIN (Gradient Index) lens and convert the beam into a good quality collimated (near gaussian) beam.

Laser Display Resolution

To discuss display resolution, let us first consider a simple focusing system from the viewpoint of ray (geometric) optics and neglect diffraction. If the light incident on a lens is collimated, represented by parallel light rays, then the lens focuses all the rays through a single point in its focal or image plane.* Since the resulting display pixel is a point, effectively we have the best imaginable resolution (infinite).



The effect of diffraction, which is a wave phenomena, from the point of view of geometric optics is to add an uncertainty $\delta\theta$ to a light ray's angle of travel beyond the lens. The magnitude of $\delta\theta$ is inversely proportional to the diameter of the light beam passsing through the lens. This uncertainty in each ray's direction results in a blurring or spreading of the convergence of the rays in the lens focal plane. As a result the display pixel has a finite size given by the product of the angular spread due to diffraction $\delta\theta$ and the lens focal length.

In this way diffraction places a fundamental limit on the resolution of any laser display. Let us model a laser scanner system as a laser with beam diameter $D=2w$ which is acted on by a scanning element which imparts an angular deflection to the beam (Figure 4). The beam exiting the scanner will have an angular spread $d\theta$, due to diffraction caused by the scanning element's finite aperture. This angular uncertainty will result in finite spot or pixel size when the beam is brought to a focus by any kind of focusing optics (including one's own eye lens system).

To further quantify this, let us define N as the number of pixels or resolvable spots in one display line. If $\Delta\Theta$ is the total angular deflection obtainable from the scanning element, then

$$N = \Delta\Theta/\delta\theta$$

is the maximum number of resolvable spots we will obtain in a line sweep through angle $\Delta\Theta$, due to the angular uncertainty $\delta\theta$ caused by diffraction. We will consider N as the measure of the scanning system's resolution.

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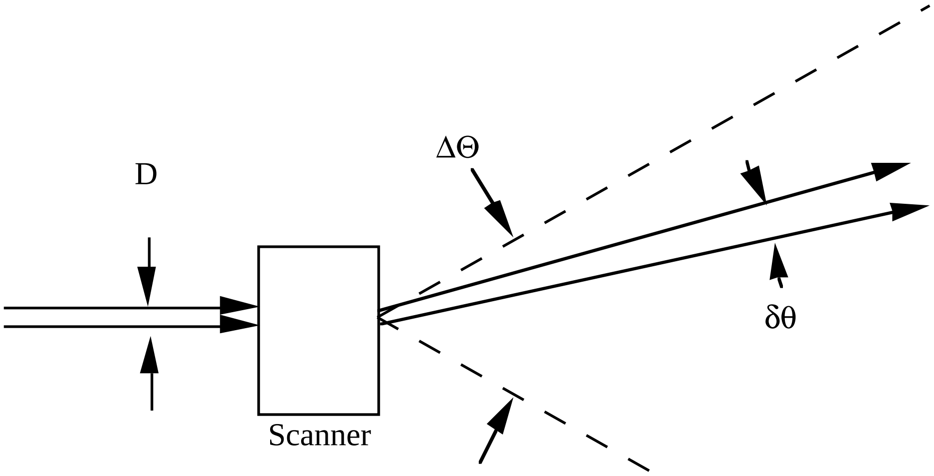
[*] For this discussion we will ignore the effects due to lens aberrations. Ultimately aberration effects must be included in determining a system's overall resolution.

In a diffraction limited system (which is the best we can do), diffraction theory[6] tells us that

$$\delta\theta \approx \lambda/D$$

where λ is the laser wavelength, and D is the aperture diameter or minimum beam diameter, whichever is smaller.



$\Delta\Theta$ = Total excursion of scanner
$\delta\theta$ = Diffractive uncertainty of deflection angle
D = Incident beam diameter

FIGURE 4

Using this expression for $\delta\theta$, we find that the number of resolved spots N in a scanned line is

$$\boxed{N \approx (\Delta\Theta \cdot D)/\lambda \qquad \text{(Equation 1)}}$$

This relationship is the starting point for evaluating the best possible resolution of any scanning system. We will use it repeatedly as we review various scanning devices. It tells us how small we can make a scanning system and still maintain a desirable resolution N and scanning range $\Delta\Theta$. For instance, if we want N=1000 and $\Delta\Theta$=60° (1 radian), then the limiting aperture D must be at least 1 mm or so in diameter. <u>It must be emphasized</u> that no additional optical manipulation, e.g. increasing total scan angle $\Delta\Theta$ using a telescope, will increase the system resolution N. For

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[6] E. Hecht and A. Zajac, <u>Optics</u>, (Addison Wesley, Reading, 1979), p. 354.

example, a telescope can be used to magnify angular deflection $\Delta\Theta$, but at the same time it will decrease the beam diameter D at the telescope focus by the same factor, leaving the product ($\Delta\Theta \cdot D$) and hence the number of resolved spots N unchanged.

In general, speed vs. resolution are competing specifications in a scanning system. In order to make a fast scanner, whether mechanical or electro-optical, we strive for small physical size. But smaller dimensions mean a smaller optical aperture D and consequently poorer resolution. Thus achieving both a fast and a high-resolution scanning system simultaneously is difficult.

Similarly, in most scanning technologies, scan speed ($d\theta/dt$) and scan range $\Delta\Theta$ are often competing specifications. This will become clear as we review some of these technologies.

Scanning Technologies

1. Rotating Polygon

Rotating polygon technology can be found in a number of scanning applications, including large screen TV[7], laser printers and target tracking.[8] The basic idea is shown in Figure 5 .

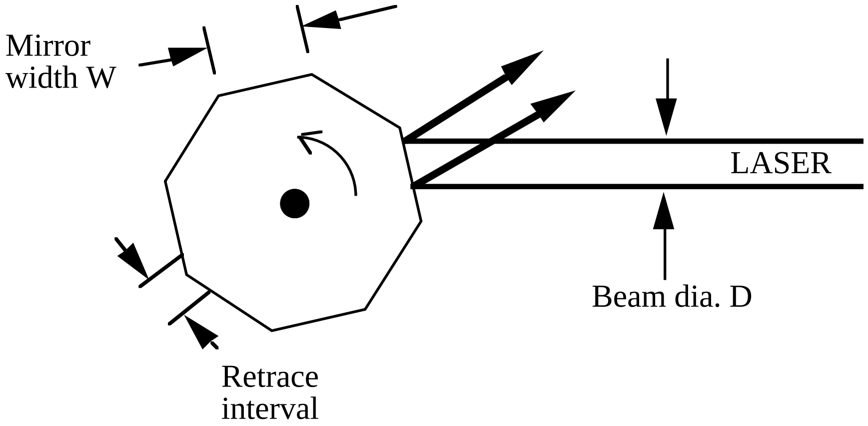

FIGURE 5

An n-sided polygon solid with mirror facets is illuminated by a narrow laser beam. As the the polygon is rotated through an angle ϕ, the laser is scanned through 2ϕ. The laser spot at the mirror facet is some fraction of the mirror width. During the "retrace" interval when the edge discontinuity between two facet mirrors passes through the incident laser, two reflected beams are produced, one at the end of the finishing scan line and the other beginning the new scan line. To reduce this retrace interval, the mirror size must be increased relative to the laser beam size.

The specifications of an n-sided polygon scanner rotating at f revolutions per second follow easily from simple geometrical optics:

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[7] S. M. Stone, J. Schlafer, and V. J. Fowler,"An Experimental Laser Color TV Projection Display System," Information Display 6, pp. 41-44 (1969).

[8] B. R. Sorenson, M. Donath, G. Yang, and R. C. Starr, "The Minnesota Scanner: A Prototype Sensor for Three-Dimensional Tracking of Moving Body Segments," IEEE Transactions on Robotics and Automation 5, pp. 499-509 (1989).

Total scan excursion $\Delta\Theta = 4\pi/n$

Angular scan rate $d\theta/dt = 4\pi f$ (radians/s)

Line scan frequency $F = f \cdot n$ (lines/s)

With single beam illumination, a polygan scanner will exhibit a "dead-time" during the time that the boundary between two adjacent facets passes through the beam, producing two reflected beams. If D is the effective diameter of the incident beam and W is the width of a facet, then only the fraction $(1 - D/W)$ of scan is useful in the sense of there being only one reflected beam. In this case we would have that the useful scan angle is given by

$$\Delta\Theta = 4\pi/n\,(1 - D/W)$$

The scanner resolution is then given from Equation 1:

$$N = (\Delta\Theta \cdot D)/\lambda$$

$$= (4\pi D/n\lambda)\,(1 - D/W)$$

which is quadratic in D. For a fixed facet width W, the maximum resolution is had when D=W/2, i.e. with 50% dead-time or using only 50% of the total scan angle of the n-sided polygon. This gives

$$N_{max} = 2\pi D/n\lambda.$$

Resolutions exceeding 1000 are possible for sufficiently large facet size D. For example a polygon with D = 1 cm and n=25 has a diffraction limited resolution of over 6000 resolvable spots.

A straightforward calculation finds that the moment of inertia I of an n-sided polygon scanner system operating at resolution N spots/line is

$$I = (\rho\, k^6 \lambda^5 N^5 n^9)/(64\pi^8)\ .$$

Here ρ is the density of the polygon material, λ is the laser wavelength, k is a geometrical factor in the range 1.5 to 2 which accounts for oblique incidence of the beam on the scanner, and the system has been assumed to be diffraction limited in determining the resolution N. The kinetic energy K.E. of such a polygon rotating to give F lines-per-second scanning rate is

$$K.E. = (\rho\, k^6 \lambda^5 N^5 n^7 F^2)/(32\pi^6).$$

To get a feel for the mechanical magnitudes involved in a TV display system, assume we want NTSC-like resolution ($N \approx 500$) with a scan rate F of 15,000 lines/sec. We'll use an aluminum polygon with 15 sides at the HeNe wavelength of 633 nm. For diffraction limited scanning the laser diameter would need to be approximately 1 mm, facet size approximately 3 x 2 mm (k=2), polygon radius around 7 mm. The rotational kinetic energy of the polygon, which is rotating at 1000 revolutions/sec (60,000 rpm!) is about 0.5 Joules. This is roughly equivalent to the kinetic energy of a one pound weight dropped from a height of 5 inches, or of a pencil dropped from the height of 12 feet. Clearly mechanical movement at these energies has potential for personal injury, particularly if utilized in a head mounted display. (Moreover, the practicality of having a 60,000 rpm head-mounted drive motor is doubtful.) Because of the strong dependence of kinetic energy K.E. on resolution N and scan rate F, the safety factor becomes even more important in a higher resolution system. Merely doubling the resolution in this example to N=1000 raises the polygon kinetic energy by a factor of 32 to 16 Joules.

On the other hand, by using a smaller polygon with fewer facets (n), the kinetic energy will drop significantly because K.E. is proportional to n to the seventh power. However, to maintain the same scan rate F, the polygon rotation rate must be increased by the same factor that the number of facets n is decreased. (Higher polygon velocities may require the use of higher strength but denser materials for the polygon.) The size and complexity of high rpm motors limits how far in this direction one can go, particularly for head mounted display applications.

The general conclusion we draw is that rotating polygons are not practical devices for a head mounted display because of safety and mechanical considerations.

2. Galvonometers

A galvonometer scanner is a mirror (usually but not necessarily flat) attached to the axial shaft of a galvonometer (Figure 6). Electric current passing through the galvonometer armature coils causes the shaft to rotate to a position determined by the electric current magnitude. Peak-to-peak mirror rotations up to 60° are possible, though requirements for speed and linearity usually limit the mirror scan to angles less than about 20°.

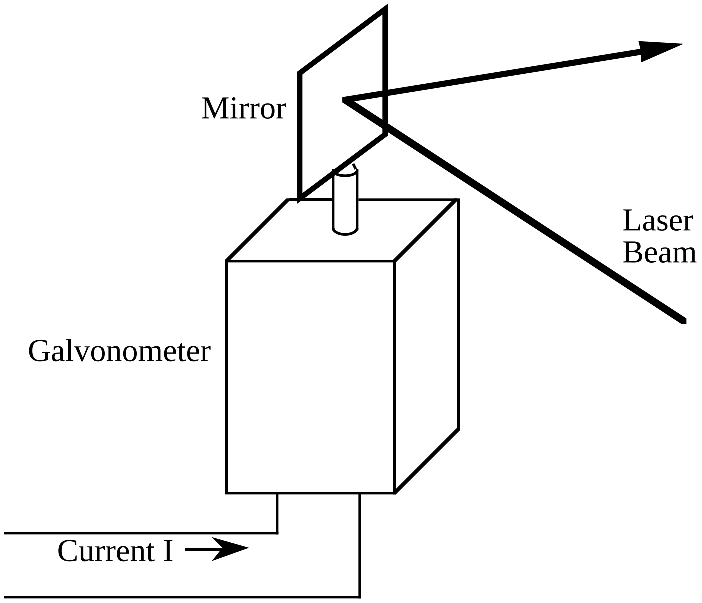

FIGURE 6

Although not capable of high frequency video (horizontal) line scanning, galvonometer scanners are quite suitable for (vertical) frame scanning. A common configuration is to use a high speed polygon or acousto-optic (see below) scanner to generate the horizontal line scans followed immediately by the slower galvonometer scanner to impart vertical deflection. Frame rates of 180 frames per second are well within the operating range of galvonometer scanners.

Unlike the polygon scanner, which mechanically is a high inertia device and most suitable for fixed frequency line scanning, the galvonometer scanner allows fixed and random beam positioning. Often a closed loop current drive circuit is used to give accurate mirror positioning. Resolutions exceeding N = 1000 are possible.

3. Piezoelectric deflectors

Probably the simplest mechanical deflection system, the piezoelectric deflector uses the bending of a stack of piezoelectric wafers fixed at one end to tilt an attached mirror. Lightweight and with no wearing parts, piezoelectric deflectors unfortunately have very small practical scan ranges, typically on order of a few milliradians (or a few minutes of arc). Commercially available units are capable of several kilohertz scan rates and line resolutions of $N \approx 1000$. These would be a very attractive technology for display systems were it not for the small scan angles (optical systems capable of angle magnification of >1000 are deemed not practical.)

4. Acousto-optic deflection

Acousto-optic or AO deflectors have been used successfully in laser TV systems.[9] Commercially available systems can be operated at NTSC video scan rates and higher.

In an AO deflector the laser beam is deflected off of an ultrasonic wave in a transparent material. As shown in Figure 7, an ultrasonic wave, typically 10^7 - 10^8 Hz, is produced in the acoustic medium, which is usually a transparent crystalline material. If the speed of sound in the medium is v at ultrasonic frequency f, the ultrasonic wavelength Λ in the medium is

$$\Lambda = v/f \ .$$

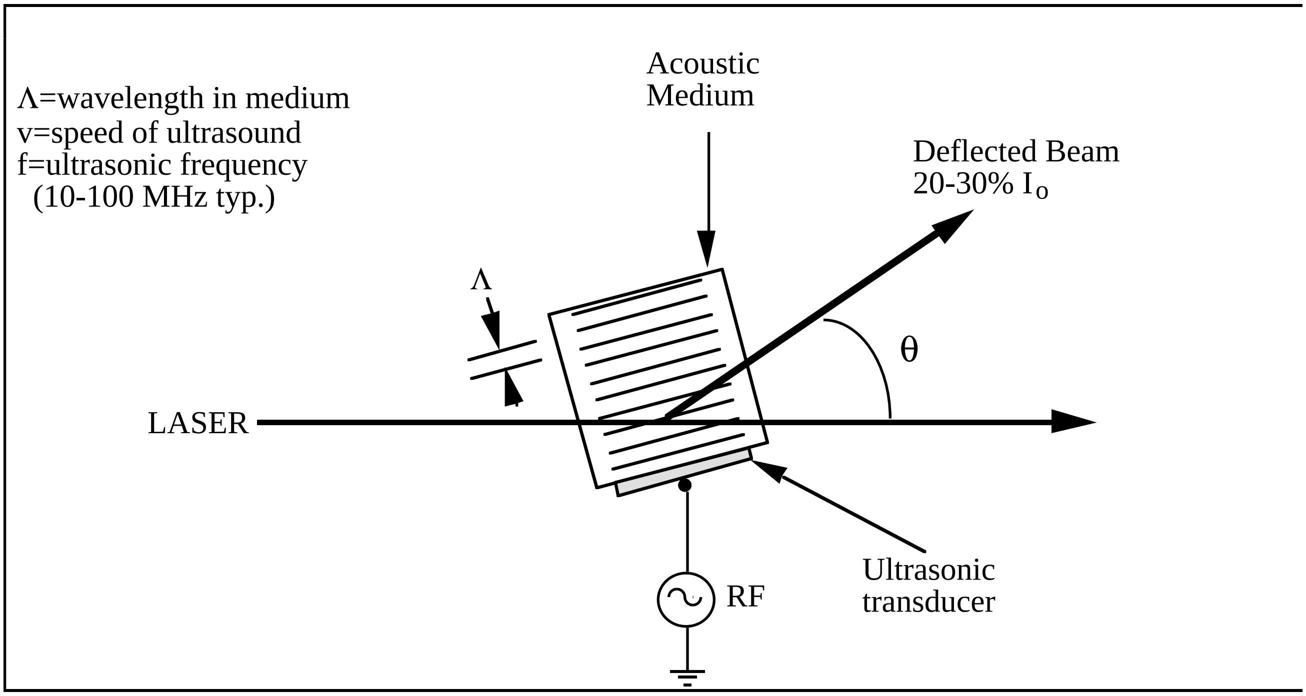

FIGURE 7

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[9] V. J. Fowler, "Laser Scanning Techniques" and references cited therein, in Laser Scanning and Recording, SPIE Vol. 378, pp. 36-49, (1985).

For an incident laser beam satisfying the Bragg condition[*], the deflected beam will emerge from the acoustic medium with the deflection angle given by[10]

$$\theta = \sin^{-1}(\lambda/\Lambda)$$
$$\approx \lambda/\Lambda$$

where the small angle approximation has been used since $\lambda/\Lambda << 1$. Relating the ultrasonic wavelength Λ to the ultrasonic frequency f and speed of sound v gives

$$\theta = \lambda \frac{f}{v}$$

The deflection angle is proportional to the ultrasonic frequency. The total scan range $\Delta\Theta$ of the deflector is determined by the ultrasonic bandwidth of the acoustic medium Δf:

$$\Delta\Theta = \lambda \frac{\Delta f}{v}$$

Thus to obtain large deflections, acoustic materials with a low speed of sound v and large acoustic bandwidths are desirable. A common material is TeO_2 with a speed of ultrasound (slow shear mode) of $v = 0.6$ mm/μs, with an acoustic bandwidth of 40 MHz. Deflection angles up to ≈2.4° (40 mrad) are obtainable with TeO_2 at the HeNe 633 nm wavelength.

The resolution of an AO scanner is determined by the usual diffraction considerations. Employing equation (1),

$$N \approx (\Delta\Theta \cdot D)/\lambda$$

$$= \left(\frac{\lambda \cdot \Delta f \cdot D}{v}\right)/\lambda$$

$$= \frac{\Delta f \cdot D}{v}$$

The quantity $\tau \equiv (D/v)$ is the "fill-time" or time required for a point in the ultrasonic wave moving at velocity v to travel across the beam diameter D. Thus we have

$$N \approx \tau\, \Delta f.$$

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[*] The Bragg condition is satisfied when the angle between the incident beam and the sound propagation direction is the same as the angle between the deflected beam and the sound propagation direction. If large deflection angles are needed, a phased array of acoustic transducers is often used to steer the acoustic wave so as to maintain the Bragg condition.

[10] E.I. Gordon, "A Review of Acousto-Optical Deflection and Modulation Devices," Proc. IEEE, Oct. 1966, pp. 1391-1401.

It has become the convention that the AO resolution is specified as the time-bandwidth product ($\tau\Delta$ f). Again using TeO_2 (Δf = 40 MHz) and taking D = 15 mm, we find τ = 16 μs and N≈975. A larger aperture size D would be needed to gain higher resolution.

We see that the AO deflector is capable of high resolution. However, there is the usual trade-off between resolution and speed of deflection. The speed with which an AO deflector can scan a laser beam is related to how quickly the ultrasound field can be changed in the volume of the sound medium overlapping the laser beam. This time is essentially the "fill-time" $\tau = D/v$ defined earlier. The shorter the fill-time t, the faster can the deflection angle be changed. Unfortunately, scan resolution N decreases with decreasing τ. To quantify this, let us assume a raster-type deflection is being employed. The ultrasonic frequency f is ramped for each successive scan as shown in Figure 8.

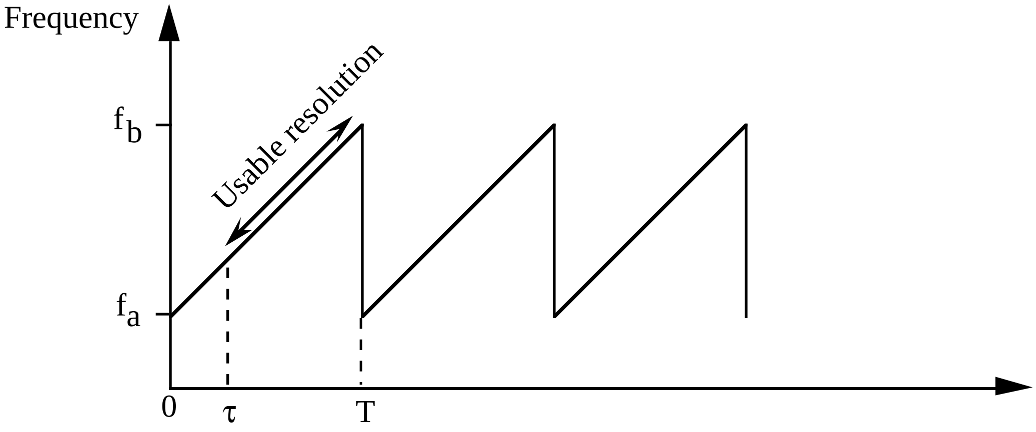

FIGURE 8

The fill-time or retrace time reduces the usable resolution by the fill-time duty-cycle:

$$N = \tau\,\Delta f\ \ (1 - (\tau/T)).$$

For fixed scan period T, the maximum resolution is obtained with τ = T/2, for which

$$N_{max} = \frac{\tau\,\Delta f}{2} = \frac{T\Delta f}{4}\ .$$

Thus as the scan speed is increased (T reduced) the scanner resolution suffers. If we take a NTSC scan period of T= 63 μs and an AO bandwidth of 100 MHz, a resolution of N ≈ 1500 is possible.

AO materials with bandwidths up to 10^9 Hz (e.g. Lithium niobate) are available at the expense of more complex drive electronics and reduced deflected beam intensity. If these costs are affordable or managable, we can estimate the best resolution possible at a frame rate of 60 Hz. For simplicity we'll assume a square display of N x N resolved spots. This allows us to specify the scan period T = 1/(60 N) (neglecting vertical retrace) and thus find

$$N = \Delta f/(4 \cdot 60 \cdot N)$$

which gives $N \approx 2000$ for $\Delta f = 10^9$ Hz. The minimum aperture size in lithium niobate ($v = 3.5$ mm/μs) to achieve this resolution is $D = 3$ cm.

Thus we have seen that the AO deflector is capable of high resolution at moderately fast scan rates. It has the additional virtue of being all solid state (no moving parts), and uses simple deflection drive (θ proportional to ultrasonic drive frequency f) and requisite electronics (VCO and rf amp, 1 Watt typical drive power).

These advantages must be balanced against certain disadvantages, notably the small deflection angles obtainable and the relatively large input aperture required for high resolution. We have seen that to achieve $N > 1000$ an aperture on the order of a few centimeters is required in the scanned dimension. For example, the IntraAction Model AOD150 ($N = 1000$) has a rectangular aperture of 41x1.3 mm. This dictates the need for beam shaping optics that transforms the circular laser beam into a 40 x 1 mm beam before it enters the AO deflector, and similar optics to retransform the deflected beam back to a circular cross section while directing it on to the following scanner element.

Additional considerations are involved in designing a color display based on acousto-optic deflectors. The deflection angle in an AO deflector is proportional to the laser wavelength λ. For a monochromatic display, this presents no difficulty. The AO acoustic medium and beam geometry are optimized for the working wavelength to give as uniform a deflection intensity as possible. A two or three color display however will in general require three separate AO deflectors, each optimized for its working wavelength. It is possible to stretch things and deflect two different wavelengths, usually red and green, using one AO. However the RF drive electronics requires a different frequency vs. deflection angle calibration for each color, and in addition for each color the deflected beam intensity will vary substantially over the deflection range.

Summary of scanning technologies

The table below summarizes the chief characteristics of the scanning techniques we have considered in this paper which are commercially available today. The list of vendors is by no means complete but merely representative of major suppliers of the indicated technology. The cost figures given are rough estimates for a 1-axis deflection system, including associated driver electronics but not including any magnification optics.

Scan technology	Resolution N (Max deflection)	Max sweep frequency (s^{-1})	Some vendors	Cost	Comments
Acousto optic	$> 10^3$ (Several degrees)	$> 10^4$	IntraAction Corp Newport ElectroOptic Systems	$5000	Most promising for fast scanning. Monochrome, color requires several deflectors.
Rotating polygon	$> 10^3$ (Tens of degrees)	$>10^4$	Lincoln Laser	$2000	Ideal for bench top scanning. Deemed mechanicallly unsuitable for HMD applications.
Galvonometer	$> 10^3$ (> 60°)	> 100	General Scanning Cambridge Technology	$1000	Suitable for slower field deflection
Piezoelectric	$> 10^3$ (< 1°)	$> 10^3$	Physik Instrumente	$6000	Small deflections, typically minutes of arc.

Video Modulation

Besides scanning the beam one must modulate the beam intensity in order to display information. The intensity of a laser diode beam can be modulated by modulating the drive current of the laser. Above the threshold current for laser action, a laser diode output power is linear with respect to changes in current to within a few percent. Modulation rates of 100 MHz are possible.

To rapidly modulate a beam from a gas laser, an external modulator is required. A modulator using an acousto-optic cell can be used for video rate modulation up to 10 or so MHz. The device is similar to the AO deflector shown in Figure 7. The intensity of the deflected beam is a (nonlinear) function of the acoustic wave amplitude in the acoustic medium.

Radiometry and Eye Safety

In a retinal scanning-based display system, like a conventional CRT display, a single display pixel or spot is written at any one time. The integration or response time of the vision system is sufficiently long that the single-spot raster scan pattern is not noticeable at the scan rates employed. Instead the full scene appears continuously illuminated. When viewing a standard CRT display, a raster scan is effectively being performed on the retina in the sense that the scanning phosphor spot produced by the CRT electron beam is imaged onto the retina by the eye optics, although the retina "spot" is effectively smeared into a line on the retina due to the non-zero fluorescence decay time of the CRT phosphor.

According to Sliney and Wolbarsht[11], the retinal irradiance of a conventional TV is on the order of 10^{-5} W/cm^2. This is the power per unit area incident on the retina due to the image of the TV screen formed on the retina. We assume that a comparable time averaged retinal irradiance is needed in the DRW system due to the laser spot scanned on the retina. We also assume the DRW field of view (per eye) is one steradian, correponding to approximately 60° x 40°. This field of view corresponds to an area on the retina of appoximately 2.8 cm^2. Thus the total power incident on the retina in the display image is (2.8 cm^2 x 10^{-5} W/cm^2) or 28 μW. At any instant, this power is all concentrated in the focused laser spot which is rapidly scanning across the retina. Therefore it is critical to address the eye safety issues associated with intrabeam viewing of a laser beam at this power level.

First we examine a worst case situation in which the laser is stationary and not scanned so that the laser power remains incident on the same retina spot. The intrabeam exposure limit[12] for 633 nm radiation for durations up to 10 seconds (which is much longer than anyone would normally stare into a harmfully bright source) is 1 mW/cm^2 (incident on the cornea surface). If we assume a 5 mm beam diameter, this gives a power limit at the cornea of 62 μW. Although this implies that our example using a 30 μW laser beam does not exceed the recommended exposure limit in this extreme case of a stationary beam, it is close enough to the limit that a safety interlock system should be incorporated to block the laser radiation in the event of a scanning system failure.

In normal operation the laser beam is constantly scanning the retina, never remaining fixed at one point on the retina. Each "pixel" on the retina is momentarily irradiated once during each raster frame scan. In effect each retina "pixel" is exposed to a pulse of laser radiation at the scan frame repetition rate (e.g. 30 pulses per second). The pulse duration can be estimated by assuming a 4 μm spot size on the retina (this is nominally the smallest image diameter possible on the retina due to diffraction and aberrations[13]) which is scanned to make a 17 mm long raster line (corresponding to 60°) across the retina. For 1000 lines scanned per frame at a frame rate of 30 Hz, this works out to approximately 10 ns for the laser spot to move 4 μm, or each 4μm diameter spot on the retina is irradiated for approximately 10 ns at a repetition rate of 30 pulses per second. (We have neglected any retrace time in the raster scan for the purposes of this approximate calculation.)

The exposure limit[14] for a pulsed laser source at 633 nm is 5×10^{-7} J/cm^2 incident on the cornea. We have been considering a 30 μW source which in 10 ns delivers 3×10^{-13} J. Incident over the area of a 2 mm pupil, this corrsponds to an energy density of 10^{-11} J/cm^2 incident on the cornea, some four orders of magnitude below the exposure limit.

Therefore a direct retina write display system does not appear to present any greater eye hazard in normal operation than other conventional display sources, provided that measures are taken to limit the laser power which reaches the cornea to an appropriate level.

Conclusion

Our analysis has shown that a display system which writes directly to the user retina without any external real image formation is possible today with off-the-shelf technology. For head mounted display purposes, weight and size constraints would likely limit such a system to being monochromatic. It would incorporate a solid state laser, acousto-optic modulator and fast deflector, and a galvonometer for slow deflection. A resolution of 1000 x 1000 pixels should be possible.

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[11] David Sliney and Myron Wolbarsht, Safety with Lasers and Other Optical Sources, (Plenum Press, New York, 1980), p. 135.

[12] Ibid, Table8-1, p. 262.

[13] Ibid, Fig. 3-11, p. 85.

[14] Ibid, Table 8-1, p.262.