Abstract

The Virtual Retinal Display (VRD) is a personal display device under development at the University of Washington's Human Interface Technology Laboratory in Seattle, Washington USA. The VRD scans light directly onto the viewer's retina. The viewer perceives a wide field of view image. Because the VRD scans light directly on the retina, the VRD is not a screen based technology.

The VRD was invented at the University of Washington in the Human Interface Technology Lab (HIT) in 1991. The development began in November 1993. The aim was to produce a full color, wide field-of-view, high resolution, high brightness, low cost virtual display. Microvision Inc. has the exclusive license to commercialize the VRD technology. This technology has many potential applications, from head-mounted displays (HMDs) for military/aerospace applications to medical society.

The VRD projects a modulated beam of light (from an electronic source) directly onto the retina of the eye producing a rasterized image. The viewer has the illusion of seeing the source image as if he/she stands two feet away in front of a 14-inch monitor. In reality, the image is on the retina of its eye and not on a screen. The quality of the image he/she sees is excellent with stereo view, full color, wide field of view, no flickering characteristics.

Introduction

Our window into the digital universe has long been a glowing screen perched on a desk. It's called a computer monitor, and as you stare at it, light is focused into a dime-sized image on the retina at the back of your eyeball. The retina converts the light into signals that percolate into your brain via the optic nerve.

Here's a better way to connect with that universe: eliminate that bulky, power-hungry monitor altogether by painting the images themselves directly onto your retina. To do so, use tiny semiconductor lasers or special light-emitting diodes, one each for the three primary colors—red, green, and blue—and scan their light onto the retina, mixing the colors to produce the entire palette of human vision. Short of tapping into the optic nerve, there is no more efficient way to get an image into your brain. And they call it the Virtual Retinal Display, or generally a retinal scanning imaging system.

The Virtual Retinal Display presents video information by scanning modulated light in a raster pattern directly onto the viewer's retina. As the light scans the eye, it is intensity modulated. On a basic level, as shown in the following figure, the VRD consists of a light source, a modulator, vertical and horizontal scanners, and imaging optics (to focus the light beam and optically condition the scan).

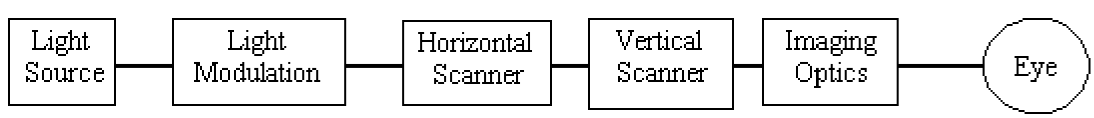

Fig1. Basic block diagram of the Virtual Retinal Display.

The resultant imaged formed on the retina is perceived as a wide field of view image originating from some viewing distance in space. The following figure illustrates the light raster on the retina and the resultant image perceived in space.

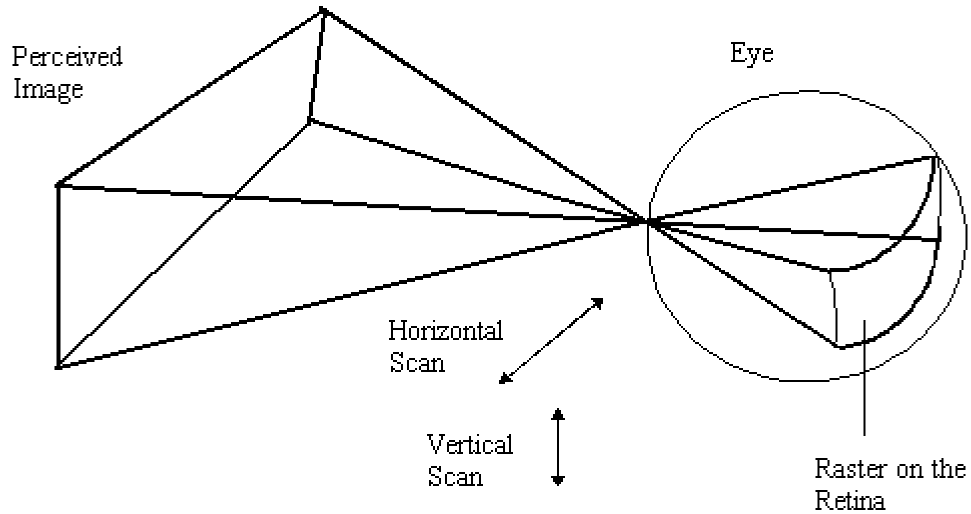

Fig2.Illustration of light raster imaged onto the retina and the resultant perceived image.

In general, a scanner (with magnifying optics) scans a beam of collimated light through an angle. Each individual collimated beam is focused to a point on the retina. As the angle of the scan changes over time, the location of the corresponding focused spot moves across the retina. The collection of intensity modulated spots forms the raster image as shown above

Potential Advantages of the Virtual Retinal Display

It is really interesting to note why this family of imaging systems score better than the conventional display systems.

Brightness

One problem with conventional helmet mounted display image sources is the low luminance levels they produce. Most liquid crystal array image sources have insufficient luminance levels for operation in a see-through display. The VRD, however, does not contain individual Lambertian (or nearly Lambertian) pixel emitters (liquid crystal cells or phosphors) as do most LCD arrays and CRT's. The only light losses in the VRD result from the optics (including the scanners and fiber coupling optics). There is no inherent tradeoff, however, between resolution and luminance as is true with individual pixel emitters. In individual pixel emitters, a smaller physical size increases resolution but decreases luminance. In the Virtual Retinal Display, intensity of the beam entering the eye and resolution are independent of each other. Consequently, the VRD represents a major step away from the traditional limitations on display brightness.

Resolution

As mentioned in the previous section there is a tradeoff between resolution and brightness in screen based displays. As resolution requirements increase, the number of picture elements must increase in a screen based display. These greater packing densities become increasingly difficult to manufacture successfully. The VRD overcomes this problem because the resolution of the display is limited only by the spot size on the retina. The spot size on the retina is determined primarily by the scanner speed, light modulation bandwidth, and imaging optics.

Yield

One limiting aspect in the manufacture of liquid crystal array image generators is the yield and reliability of the hundreds of thousands of individual liquid crystal cells present in these displays. For a liquid crystal array display to function properly at all times, each picture element must function properly. The Virtual Retinal Display requires only constant functionality from the light sources and the scanners. As resolution increases in virtual image displays, liquid crystal arrays will contain more and more individual liquid crystal cells. The Virtual Retinal Display will gain an increasing advantage over liquid crystal array image generators in terms of yield as resolution demands increase in the future.

Size

The theoretical size for horizontal and vertical scanners plus light sources for the VRD is smaller than the size of conventional liquid crystal array and CRT image sources. A typical size for a liquid crystal array image generator for helmet mounted display applications is one inch by one inch. The Mechanical Resonant Scanner used in this project was approximately 1 [cm] by 2 [cm]. Furthermore, the problem of scanner size has not been directly addressed. Further size reduction is certainly possible. It should be noted that light sources for a smaller, usable full color VRD must be much smaller than the sources used in this project. The potential size of light emitting diodes and diode lasers indicate that these sources show greatest promise for future systems in terms of size.

Moreover, it will be quite surprising to know that the original stereographic display, or the three dimensional view as the eye means it, can be accomplished only by an imaging system like the one proposed above.

Fundamentals of human eye

The eye is a specialized organ that is capable of light reception, and in the case of vertebrates, is able to receive visual images and then carry it to the visual centre in the brain. The horizontal sectional view of human eye is as follows (courtesy Encyclopedia Britannica 2002)

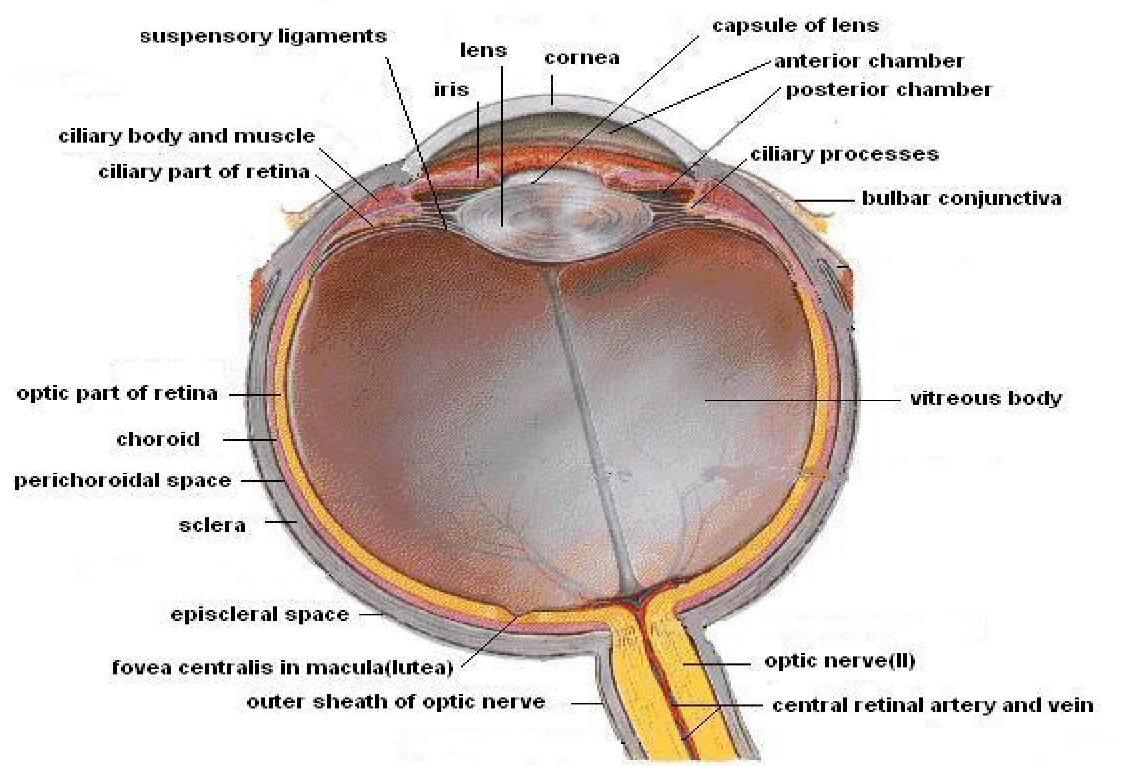

Fig3. The cross sectional view of the human eye

The eyeball is generally described as a globe or a sphere, but it is oval, not circular. It is about an inch in diameter, transparent in front, and composed of three layers.

1) The outer fibrous, the supporting layer
2) Middle, vascular, and
3) Inner nervous layer.

Six muscles move the eye, four straight and two oblique. These lie inside the orbit passing from the bony walls of the orbit to be attached to the sclerotic coat of the eye behind the cornea. The movements of the eyes are combined, both eyes move to right or left, up, and down, etc. Normally the axes of both the eyes converge simultaneously on the same point; when owing to paralysis of one or more muscles, they fail to do so squint exists.

The Sclera is the tough outer fibrous coat. It forms the *white of the eye* and is continuous in front with the transparent window membrane, the *cornea.* The sclera protects the delicate structures of the eye and helps to maintain the shape of the eyeball.

The Choroid or middle vascular coat contains the blood vessels, which are the ramifications of the ophthalmic artery, a branch of the internal carotid. The vascular coat forms the *iris* with the central opening or *pupil* of the eye. The pigmented layer behind the iris gives its colour and determines whether the eye is blue, brown, grey etc. The horoids is continuous in the front with the iris and just behind the iris this coat is thickened to form the *ciliary body*, thus the ciliary body lies between the choroids and the iris. It contains circular muscle fibres and radiating fibres; contraction of the former contracts the pupil of the eye.

The Retina is the inner nervous coat of the eye, composed of a number of layers of fibres, nerve cells, rods and cones, all of which are included in the construction of the retina, the delicate nerve tissue conducting the nerve impulses from without inwards to the *optic disc*, the point where the optic nerve leaves the eyeball. This is the blind spot, as it possesses no retina. The most acutely sensitive part of the retina is the *macula,* which lies just external to the optic disc, and exactly opposite the centre of the pupil.

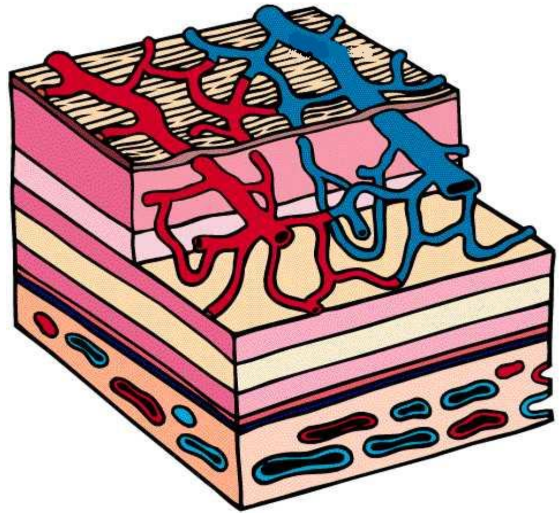

Fig4.The layered view of retina showing blood vessels

The retina is the nervous mechanism of sight. It contains the endings of the optic nerves, and is comparable to a sensitive photographic plate.

When an image is perceived, rays of light from the object seen pass through the cornea, aqueous humour, lens, and vitreous body to stimulate the nerve endings in the retina. The stimuli received by the retina pass along the optic tracts to the visual areas of the brain, to be interpreted. Both areas receive the message from both eyes, thus giving perspective and contour.

In ordinary camera one lens is provided. In the eye, whilst the crystalline lens is very important in focusing the image on the retina, there are in all four structures acting as lenses: the cornea, the aqueous humour, the crystalline lens, and the vitreous body.

As in all interpretations of sensation from the surface, a number of relaying stations are concerned with the transmission of the senses which in this case is the sight. A number of these relaying stations are in the retina. Internal to the periphery of the retina are layers of rods and cones which are highly specialized sight cells sensitive to light. The circular interruptions in these are termed as granules. The proximal ends of the rods and cones form the first synapse with a layer if bipolar cells, still in the retina. The second processes of these cells form the second nerve synapse with large ganglion cells, also in the retina. The axons of these cells form the fibres of the optic nerve. These pass backwards, first reaching the lower centre in special bodies near the thalamus, and finally reaching the special visual centre in occipital lobe of cerebral hemisphere where sight is interpreted.

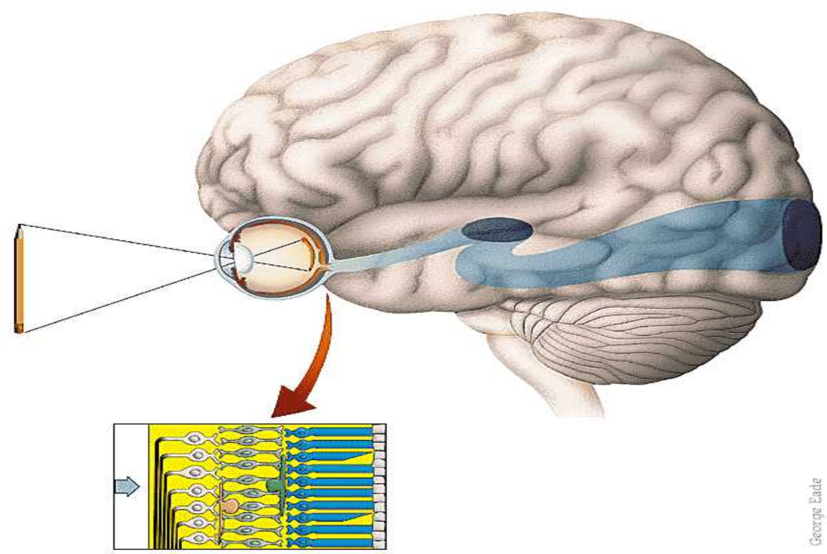

Fig5. The Human visual pathway

Each retina includes multiple mosaics of neurons that separately represent the visual field. Image transduction uses two systems of photoreceptors: the rods and cones. Each system comprises a separate sampling mosaic of retinal image. The rods encode the data for a system with low spatial resolution but high quantum efficiency. The cones encode the image data at much higher spatial resolution and lower quantum efficiency.

Rods and cones generally operate under different viewing conditions, but there are also many cases in which multiple representations of the image are obtained under a single viewing condition. For example, the cones can be subdivided into three sampling mosaics that expand the spectral encoding. The three cone mosaics also differ in their spatial sampling properties.

History of Virtual Retinal Display

The VRD display concept was initially conceived by Dr. Thomas A. Furness as a means of eliminating large aperture optics and expensive high-resolution addressable images sources such as CRTs. Soon after joining the HIT Lab in 1991, Joel Kollin realized a key feature about the VRD - movements of the eye would not result in perceived movement in the image. Therefore, eye tracking would not be necessary beyond that what might be needed to ensure that the light beam entered the eye. He then designed and constructed the original bench-mounted VRD, using an acousto-optic device as the horizontal scanner. Electronics largely designed and built by Bob Burstein then allowed it to be driven directly by a DEC workstation, although it was still significantly lower in both contrast and resolution than a standard SVGA display and offered an image only in uncalibrated shades of red. We subsequently began work on patenting the display and brought on board David Melville to engineer the mechanical design, especially a new scanning system. In 1993, a newly formed corporation, MicroVision Inc., licensed the VRD technology and signed a 4 year, $5.1 million development contract with the University. Rich Johnston was hired specifically to manage the VRD and other hardware products of the Lab. By forming relationships with other researchers in the College of Engineering, he has orchestrated a program to solve the challenges and bottlenecks of the project.

In late 1993 and 1994, Mike Tidwell redesigned the VRD to maximize the resolution possible with the A-O scanner while David Melville designed a new Mechanical Resonant Scanner (MRS) which would be capable of the high rates of horizontal scanning without the costs and other limitations of the A-O devices. The MRS was then utilized in full-color inclusive and "see-through" systems.

Virtual Retinal Display- A system overview

The VRD can be considered a portable system that creates the perception of an image by scanning a beam of light directly into the eye. Most displays directly address a real image plane (typically a CRT or matrix-addressed LCD) which might be relayed to form a larger, more distant image for a head-mounted display (HMD). The VRD uses a scanned, modulated light beam to treat the retina as a projection screen, much as a laser light show would use the ceiling of a planetarium. The closest previously existing device would be the scanning laser opthalmoscope (SLO) which scans the retina to examine it; the SLO is designed to capture light returning from the eye whereas the VRD is designed as a portable display..

The VRD has several advantages over CRTs, LCD, and other addressable-screen displays:

- Resolution is limited by beam diffraction and optical aberrations, not by the size of an addressable pixel in a matrix. Very high resolution images are therefore possible without extensive advances in micro-fabrication technology. Also, the VRD does not suffer from pixel defects.
- The display can be made as bright as desired simply by controlling the intensity of the scanned beam. This makes it much easier to use the display in "see-though" configuration on a bright day.
- The scanning technology in the current display requires only simple, well understood manufacturing technology and can therefore be manufactured inexpensively.
- Because the light is projected into the eye and the scanner is electro-mechanically efficient, the display uses very little power.
- In theory, the VRD allows for accommodation to be modulated pixel by pixel as the image is being scanned.

All components in the VRD are small and light, making them ideal for use in a portable display.

The Basic System

In a conventional display a real image is produced. The real image is either viewed directly or, as in the case with most head-mounted displays, projected through an optical system and the resulting virtual image is viewed. The projection moves the virtual image to a distance that allows the eye to focus comfortably. No real image is ever produced with the VRD. Rather, an image is formed directly on the retina of the user's eye. A block diagram of the VRD is shown in the figure below.

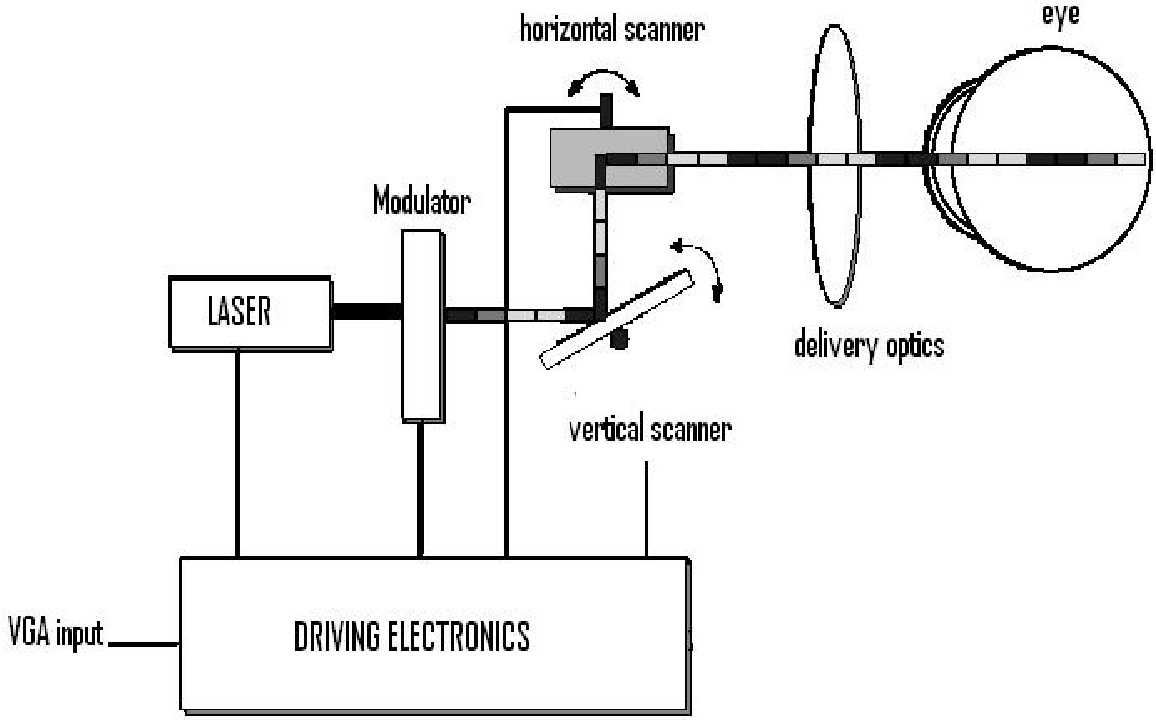

Fig6. The functional block diagram of a VRD system

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 coherent 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. A variety of scan patterns are possible. The scanner could be used in a calligraphic mode, in which the lines that form the image are drawn directly, or in a raster mode, much like standard computer monitors or television. 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 into the eye. 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 beam on the retina, forming a spot. The position on the retina where the eye focuses the spot is determined by the angle at which light enters the eye. This angle is determined by the scanners and is continually varying in a raster pattern. The brightness of the focused spot is determined by the intensity modulation of the light beam. The intensity modulated moving spot, focused through the eye, draws an image on the retina. The eye's persistence allows the image to appear continuous and stable.

Finally, the drive electronics synchronize the scanners and intensity modulator with the incoming video signal in such a manner that a stable image is formed

VRD Features

The following sections detail some of the advantages of using the VRD as a personal display.

Size and Weight

The VRD does not require an intermediate image on a screen as do systems using LCD or CRT technology. The only required components are the photon source (preferably one that is directly modulatable), the scanners, and the optical projection system. Small photon sources such as a laser diode can be used. As described below the scanning can be accomplished with a small mechanical resonant device developed in the HITL. The projection optics could be incorporated as the front, reflecting, surface of a pair of glasses in a head mount configuration or as a simple lens in a hand held configuration. HITL engineers have experimented with single piece Fresnel lenses with encouraging results. The small number of components and lack of an intermediate screen will yield a system that can be comfortably head mounted or hand held.

Resolution

Resolution of the current generation of head mounted and hand held display devices is limited by the physical parameters associated with manufacturing the LCDs or CRTs used to create the image. No such limit exists in the VRD. The limiting factors in the VRD are diffraction and optical aberrations from the optical components of the system, limits in scanning frequency, and the modulation bandwidth of the photon source.

A photon source such as a laser diode has a sufficient modulation bandwidth to handle displays with well over a million pixels. If greater resolution is required multiple sources can be used.

Currently developed scanners will allow displays over 1000 lines allowing for the HDTV resolution systems. If higher resolutions are desired multiple sources, each striking the scanning surface at a different angle, can be used.

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Field of View

The field of view of the VRD is controlled by the scan angle of the primary scanner and the power of the optical system. Initial inclusive systems with greater than 60 degree horizontal fields of view have been demonstrated. Inclusive systems with 100 degree fields of view are feasible. See through systems will have somewhat smaller fields of view. Current see through systems with over 40 degree horizontal fields of view have been demonstrated.

Color and Intensity Resolution

Color will be generated in a VRD by using three photon sources, a red, a green, and a blue. The three colors will be combined such that they overlap in space. This will yield a single spot color pixel, as compared to the traditional method of closely spacing a triad, improving spatial resolution.

The intensity seen by the viewer of the VRD is directly related to the intensity emitted by the photon source. Intensity of a photon source such as a laser diode is controlled by the current driving the device. Proper control of the current will allow greater than ten bits of intensity resolution per color.

Brightness

Brightness may be the biggest advantage of the VRD concept. The current generations of personal displays do not perform well in high illumination environments. This can cause significant problems when the system is to be used by a soldier outdoors or by a doctor in a well lit operating room. The common solution is to block out as much ambient light as possible. Unfortunately, this does not work well when a see through mode is required.

The VRD creates an image by scanning a light source directly on the retina. The perceived brightness is only limited by the power of the light source. Through experimentation it has been determined that a bright image can be created with under one microwatt of laser light. Laser diodes in the several milliwatt range are common. As a result, systems created with laser diode sources will operate at low laser output levels or with significant beam attenuation.

Power Consumption

The VRD delivers light to the retina efficiently. The exit pupil of the system can be made relatively small allowing most of the generated light to enter the eye. In addition, the scanning is done with a resonant device which is operating with a high figure of merit, or Q, and is also very efficient. The result is a system that needs very little power to operate.

A True Stereoscopic Display

The traditional head-mounted display used for creating three dimensional views projects different images into each of the viewer's eyes. Each image is created from a slightly different view point creating a stereo pair. This method allows one important depth cue to be used, but also creates a conflict. The human uses many different cues to perceive depth. In addition to stereo vision, accommodation is an important element in judging depth. Accommodation refers to the distance at which the eye is focused to see a clear image. The virtual imaging optics used in current head-mounted displays place the image at a comfortable, and fixed, focal distance. As the image originates from a flat screen, everything in the virtual image, in terms of accommodation, is located at the same focal distance. Therefore, while the stereo cues tell the viewer an object is positioned at one distance, the accommodation cue indicates it is positioned at a different distance.

With the VRD it is theoretically (this is currently in the development stage) possible to generate a more natural three dimensional image. The VRD has an individual wavefront generated for each pixel. It is possible to vary the curvature of the wavefronts. Note that it is the wavefront curvature which determines the focus depth. This variation of the image focus distance on a pixel by pixel basis, combined with the projection of stereo images, allows for the creation of a more natural three-dimensional environment.

Inclusive and See Through

Systems have been produced that operate in both an inclusive and 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 a see through mode when used in a medium to high illumination environment where the luminance can reach ten thousand candela per meter squared. As discussed above, this is not a problem with the VRD.

In the VRD a light source is modulated with image information, either by direct power ("internal") modulation or by an external modulator. The light is passed through an x-y scanning system, currently the MRS and a galvanometer. Light from the scanner pair enters an optical system, which in present implementations of the VRD forms an aerial image and then uses and eyepiece to magnify and relay this image to infinity.

Components of the Virtual Retinal Display

Video Electronics

In its current form, the video electronics of the VRD controls the light intensity modulation, scanner deflection, and the synchronization between modulation and scanning. The horizontal and vertical synchronization signals in the video signal are used to determine scanner synchronization. A user selectable delay of up to one full line is incorporated into the video electronics to allow for phase difference between the horizontal scanner position and the modulation timing. Also, the respective drive levels for intensity modulation of each light source are output from the electronics.

The drive electronics control the acousto-optic modulators that encode the image data into the pulse stream. The color combiner multiplexes the individually-modulated red, green, and blue beams to produce a serial stream of pixels, which is launched into a single mode optical fiber to propagate to the scanner assembly. The drive electronics receive and process an incoming video signal, provide image compensation, and control image display. For VGA projection, the electronics process over 18 Mpix/s. The virtual retinal display is capable of providing UXGA resolution of 1600 x 1200 or 115 Mpix/s.

Light Sources and Modulators

The light sources for the VRD generate the photons which eventually enter the eye and stimulate the photo receptors in the retina. The modulation of the light source determines the intensity of each picture element. The size of the scanning spot and the rate at which it can be modulated determine the effective size of each picture element on the retina. As the light is scanned across the retina, the intensity is synchronized with the instantaneous position of the spot thereby producing a two dimensional pattern of modulated light that is perceived as a picture.

According to conventional additive color theory, any color can be represented as a mixture of three appropriately chosen primaries. The three ideal VRD light sources would be monochromatic for maximum possible color saturation.. Spatial coherence is also important - larger source spots will correspond to larger spots on the retina, decreasing resolution. The primary cause of the real (if sometimes exaggerated) hazards of laser light are the result of spatially coherent light focusing to a small area on the retina, causing highly localized heating and ablation of tissue. In the VRD the spot is traveling in two directions and even when stationary is not at a power level that would cause damage. We are working with ophthalmologists and will publish a definitive article on this in the near future. Incidentally, polychromatic sources can be shown to form spots comparable to monochromatic ones of the same spatial extent. Therefore spatial coherence is responsible for the small spot size which leads to both high resolution and (given enough power) retinal hazard.

To achieve the desired resolution, all current VRD prototypes have used lasers for their superior spatial coherence characteristics. In order to use a point source such as an LED, the image of the source should be smaller than the diffraction limit of the scanner. Using the lens magnification, one can determine the maximum source size that can be used before degrading the diffraction limited spot size at the image plane. The angular divergence of the source is effectively limited by treating the scanner as a stop. Light which does not hit the mirror does not contribute to the image plane spot size. From this geometric argument we can derive an equivalent point source size between 4 and 5 microns for a VGA resolution image in our current system. For a system where the scanner is illuminated with a collimated Gaussian beam, similar arguments can be made to determine the required divergence and beam waist from the equations for image plane spot size.

The light source module contains laser light sources, acousto-optic modulators to create the pulse stream, and a color combiner that multiplexes the pulse streams. To provide sufficient brightness, full-color displays suitable for outdoor, daylight applications incorporate red diode lasers (635nm), green solid-state lasers (532 nm), and blue solid-state or argon gas lasers (450-470 nm range). Systems designed for indoor use can incorporate LEDs; red, blue, and green devices currently under development for such systems are being tested. Generally, the energy levels are on the order of nanowatts to milliwatts, depending on display requirements. The levels of light involved are well within laser safety standards for viewing, as confirmed by analysis.

Generally two types of intensity modulation of lasers are done in existing designs. They are Laser diode modulation and acousto-optical modulation. The laser diode modulation is generally used for red laser. The small rise time of the solid state diode laser device allows high bandwidth (up to 100[MHz]) analog modulation. The video electronics regulate the voltage seen by the laser current driver and it controls the current passing through the laser which in turn controls the light output power from the laser. The laser diode is operated between amplitudes of 0.0 and 80.0[mA].

Acousto-optic (A-O) modulators intensity modulate the green and blue laser beams. Acousto-optic modulators create a sound wave grating in a crystal through which a light beam passes. The sound wave creates alternate regions of compression and rarefaction inside the crystal. These alternating regions locally change the refractive index of the material. Areas of compression correspond to higher refractive indices and areas of rarefaction correspond to lower refractive indices. The alternating areas of refractive index act as a grating and diffract the light. As the sound wave traverses the light beam, the diffracted beam is intensity modulated according to the amplitude modulated envelope on the carrier signal.

Scanners

The scanners of the VRD scan the raster pattern on the retina. The angular deviation of the horizontal scanner combined with the angular magnification of the imaging optics determines the horizontal field of view. The angular deviation of the vertical scanner combined with the angular magnification of the imaging optics determines the vertical field of view. The horizontal scanner speed and the frame rate determine the number of horizontal lines in the display, *Number of horizontal lines = horizontal scanner frequency / frame rate*,

where frame rate is the number of times per second the entire picture (or frame) is generated. The modulation rate and the horizontal scanner frequency determine the number of pixels per line in the display,

Number of pixels per line = modulation frequency / horizontal scanner frequency,

where the modulation frequency is the number of times per second the pixels are created (or modulated).

The horizontal scanning mechanism of the VRD must be capable of both relatively high scan rates (15 kHz-90+ kHz) and high resolution (500-2000+ pixels) for NTSC to HDTV formats, respectively. SVGA format systems (80 kHz) in monochrome/greyscale using an A-O scanner and 30 kHz in full-color with a mechanical resonant one have been built.

The scanning device consists of a mechanical resonant scanner and galvanometer mirror configuration. The horizontal scanner is the mechanical resonant scanner (MRS)]. The MRS has a flux circuit induced by coils which are beneath a spring plate. The flux circuit runs through the coils and the spring plate and alternately attracts opposite sides of the spring plate and thereby moves the scanner mirror through an angle over time. In a design developed at the HITL the vertical deflection mirror was chosen as the galvanometer mirror. The galvanometer deflection can be selected according to the aspect ratio of the display and a typical ratio of 4:3 can be chosen. The galvanometer frequency is controlled by the video electronics to match the video frame rate.

The galvanometer and horizontal scanner are arranged in what is believed to be a novel configuration such that the horizontal scan is multiplied. The scanners are arranged, as shown in the following figures. Such that the beam entering the scanner assembly first strikes the horizontal scanner then strikes the vertical scanner. The beam is reflected by the vertical scanner back to the horizontal scanner before exiting the scanner assembly. The beam therefore strikes the horizontal scanner twice before exiting the scanner configuration. In such an arrangement, the first scan (corresponding to the first bounce or reflection) is doubled by the second scan (corresponding to the second bounce or reflection). The case shown is for $\theta = 45$ [deg.] wherein the exit beam returns parallel to the horizontal incident beam. In the first figure the MRS is undeflected and in the latter the MRS is deflected by δ [deg.].

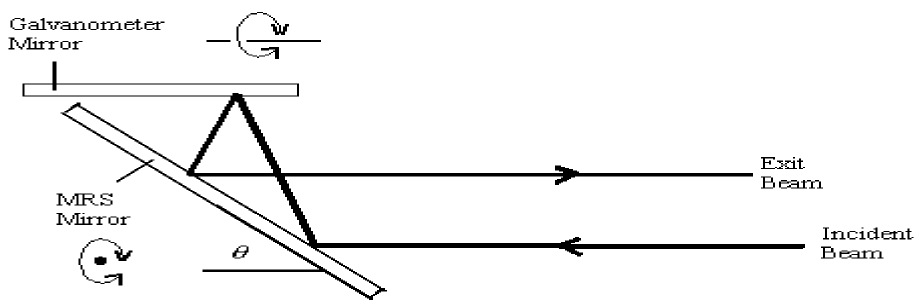

Fig7. MRS/Galvanometer scanner assembly showing incident and exit beam paths for the MRS in an undeflected position.

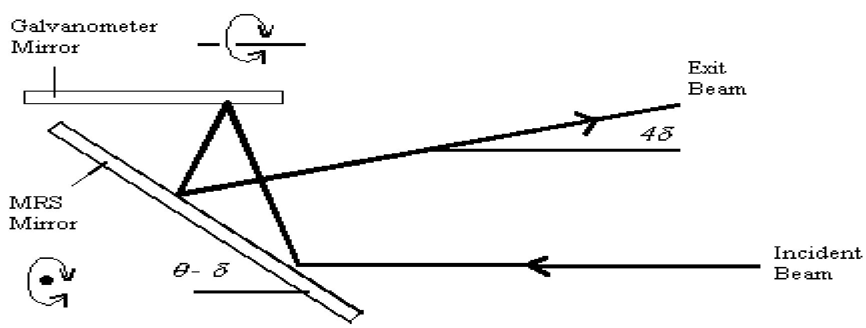

Fig8. MRS/Galvanometer scanner assembly showing incident and exit beam paths for the MRS in a deflected position.

The result of arranging the scanners as in the above figures is a doubling of the horizontal optical scan angle. Other configurations have been applied to this approach to achieve a tripling in the horizontal direction and simultaneously a doubling in the vertical direction.

For more compact designs, techniques from micro electro-mechanical systems maybe utilized in the fabrication of scanners. The electrostatic actuation of a MEMS scanner had been developed. By etching thin layers from a sliver of silicon, the researchers were able to build a scanner that weighs a mere 5 grams and measures less than 1 square centimeter. The mirror, too, is much smaller at 1 millimeter across and is mounted on the end of a thin, flexible, bar which is anchored to the silicon. The mirror is turned into one plate of a capacitor, with the other plate formed by a small area of silicon beneath it. Put a rapidly varying voltage across the two plates and then the mirror will be first repelled and then attracted. The mirror can move up or down more than 30,000 times each second.

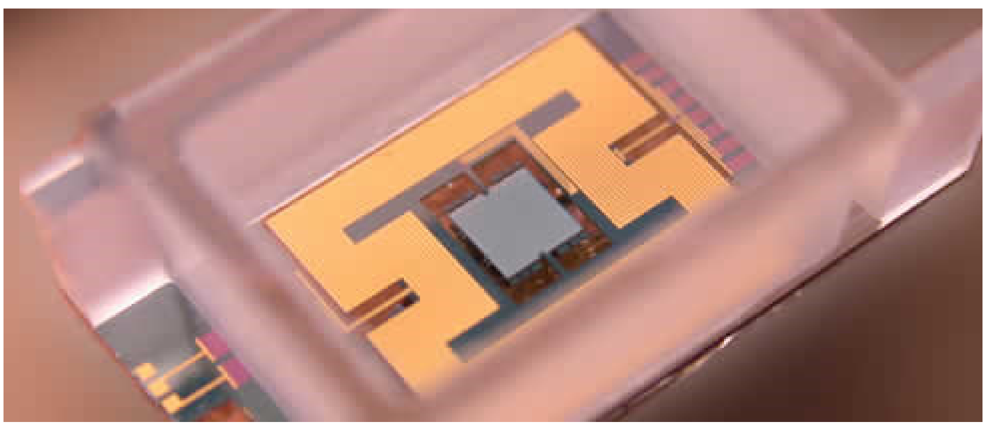

Fig9. A MEMS mirror

Micro-Electro-Mechanical Systems (MEMS) is the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through the utilization of microfabrication technology. The electronics are fabricated using integrated circuit (IC) process sequences, while the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices.

The electromagnetic actuation of the scanners yields more life to the system and imparts more torque. Such designs have also been developed for retinal scanning displays.

Pupil expander

Nominally the entire image would be contained in an area of 2 mm2. The exit-pupil expander is an optical device that increases the natural output angle of the image and enlarges it up to 18 mm on a side for ease of viewing. The raster image created by the horizontal and vertical scanners passes through the pupil expander and on to the viewer optics. For applications in which the scanned-beam display is to be worn on the head or held closely to the eye, we need to deliver the light beam into what is basically a moving target: the human eye. Constantly darting around in its socket, the eye has a range of motion that covers some 10 to 15 mm. One way to hit this target is to focus the scanned beam onto exit pupil expander. When light from the expander is collected by a lens, and guided by a mirror and a see-through monocle to the eye, it covers the entire area over which the pupil may roam. For applications that require better image quality using less power, we can dispense with the exit pupil expander altogether either by using a larger scan mirror to make a larger exit pupil or by actively tracking the pupil to steer light into it.

Viewer optics

The viewer optics relay the scanned raster image to the oculars worn by the user. The optical system varies according to the application. In the case of military applications such as helmet mounted or head mounted display optics, the system incorporates glass and or plastic components; for medical applications such as image-guided surgery, head-mounted plastic optics are used. In industrial or personal displays, the optics might be a simple plastic lens. A typical viewing system that was employed in a VRD developed at HITL is as follows.

The viewing optics, or the optics through which the user sees the intended image, are diagrammed in the following figure. The convergent tri-color beams emanating from the scanner pass (partially) through a beamsplitter. The beamsplitter (or beamsplitter/combiner) is coated such that 40% of any light striking it is reflected and 60% is transmitted. The transmittance/reflectance is somewhat angle dependent but this dependence is not severe. On first pass, 60% of the energy in the scan is transmitted through the splitter/combiner to a concave spherical mirror. The mirror is actually a rectangular section of a spherical mirror with radius of curvature -100 [mm]. The negative sign denotes concavity .

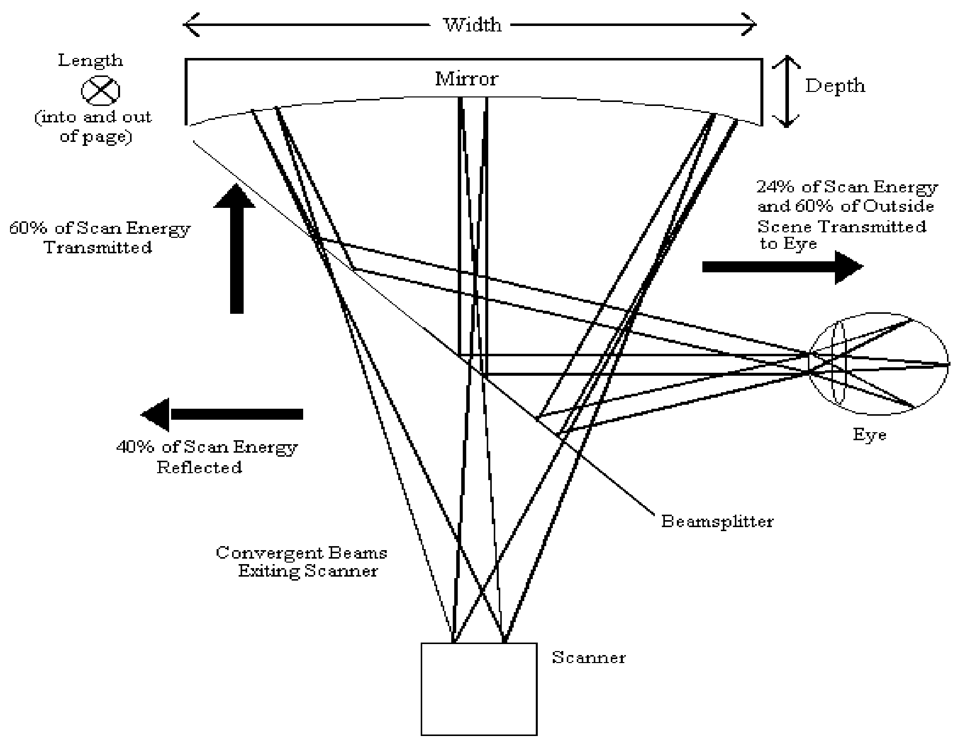

Fig10. The viewing optics system of VRD

Holographic Optical Element

One of the problems with the VRD only becomes apparent when you put it on. It can be likened to looking through a pair of high- magnification binoculars that one must line his eyes precisely with the beam or the image disappears. Since we rarely fix our eyes on a single point for more than few seconds, using VRD becomes difficult. So en eye-tracking system that follows the movements of the pupil by monitoring the reflections from the cornea had to be developed. The tracker calculates where the eye is looking and moves the laser around to compensate. But this system is complex and expensive.

A better solution may lie with a special kind of lens known as a holographic optical element. An HOE is actually a diffraction grating made by recording a hologram inside a thin layer of polymer.

It works by converting a single beam of laser into a circular array of 15 bright spots. Place the HOE between the scanning mirrors and the eye, and the array of beams that forms will illuminate the region round your pupil. Move your eyes slightly and one of the beams will still strike the cornea and be focused to form an image on the retina. HOEs have a big advantage over eye tracking systems: because they are made from a thin layer of polymer, they weigh next to nothing. "All of the action takes place in a layer just a fraction of millimeter thick", says a researcher.

Estimated Retinal Illuminance

The relationship between estimated retinal illuminance and scene luminance is important in understanding the display operating on this principle. As the display in this thesis contains no screen or real object, it is impossible to discuss the brightness of the display in terms of luminance. In terms of brightness, estimated retinal illuminance is a common denominator, so to speak, of screen based display systems and retinal scanning displays systems. The estimated retinal illuminance is [36]:

I (trolands) = R x pupil area (mm^2) x scene luminance (cd/m^2)

where I = retinal illuminance, "pupil area" refers to the area of the pupil of the eye, and

R = the effectivity ratio. The effectivity ratio, R, allows for the Stiles-Crawford effect and is,

$R = 1 - 0.0106d^2 + 0.0000416d^4$.

where d = the eye's pupil diameter in millimeters. As shown by dimensional analysis on the equation for I , trolands reduce effectively to the units of optical power per unit steradian.

The Stiles-Crawford effect describes the contribution to brightness sensation of light entering different points of the pupil (i.e. light entering the center of the pupil contributes more to the sensation of brightness than does light entering farther from the pupil center). Some standard scene luminance values, L, and their corresponding Stiles-Crawford corrected estimated retinal illuminance values, I, are given in Table II.1 [36,37].

Type of Scene	Approximate Luminance [cd/m^2]	Estimated Retinal Illuminance [trolands]
Clear day	10^4	3.0×10^4
Overcast day	10^3	4.5×10^3
Heavily overcast day	10^2	9.5×10^2

Sunset, overcast day	10	1.5×10^{2}
1/4 hour after sunset, clear	1	20
1/2 hour after sunset, clear	10^{-1}	2.0
Fairly bright moonlight	10^{-2}	0.23
Moonless, clear night sky	10^{-3}	2.7×10^{-2}
Moonless, overcast night sky	10^{-4}	3.0×10^{-3}

Table1. Standard scene luminance values and corresponding estimated retinal illuminance values.

Transmission Characteristics of the Ocular Media

Transmission losses in the eye result from scattering and absorption in the cornea, lens, aqueous humor, and vitreous humor. The transmittance of the ocular media is a function of the wavelength of the light traveling through the media. Figure 2.2 shows a plot of the total transmittance of the ocular media as a function of wavelength [38].

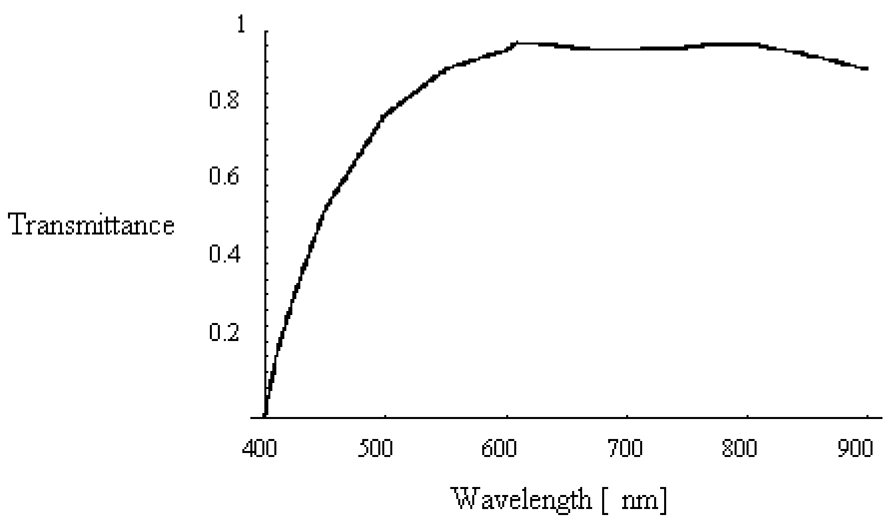

Fig11. Transmittance of the ocular media vs. wavelength.

Image Quality as Related to the Eye

Introduction

Measurements of display image quality depend heavily on two display characteristics, resolution and "contrast" (see subsequent sections). It is virtually fruitless to discuss image quality in terms of either resolution or "contrast" without including the other. Definitions for display resolution, contrast, contrast ratio, and modulation contrast are given in the following discussion. Whenever possible, the meanings of the terms are related to the effect or result at the retina.

Display Resolution and the Eye

The resolution of a display can be defined as the angle subtended by each display resolution element. For a screen (CRT or LCD) based display, the angular extent of each pixel element determines the resolution. For the VRD, the angular extent of each spot on the retina dictates the system resolution. A spot of extent *h* on the retina allows for an angular resolution of,

$\theta \tan^{-1}[h/f_{eye}]$

where f_{eye} is the focal length of the eye. Display resolution is often measured in cycles per degree for periodic gratings such as bar patterns or sinusoidal gratings.

Display Contrast and the Eye

The contrast, *C*, of a display is the ratio of the difference between the maximum display intensity and the minimum display intensity divided by the maximum. In other terms [40],

$C = (L_{Dmax} - L_{Dmin}) / L_{Dmax}$

where L_{Dmax} = the maximum display luminance and L_{Dmin} = the minimum display luminance. Extending the definition of contrast in terms of estimated retinal illuminance gives

$C = (I_{Dmax} - I_{Dmin}) / I_{Dmax}$.

where I_{Dmax} = the maximum estimated retinal illuminance due to the display and I_{Dmin} = the minimum estimated retinal illuminance due to the display. In other words, the values of I_{Dmax} and I_{Dmin} correspond to the estimated retinal illuminance values of displays with luminance values of L_{Dmax} and L_{Dmin} respectively. In the case of a retinal scanning display, as in this thesis, estimated retinal illuminance is a preferable measure of display brightness as there is no screen in the system.

Display Contrast Ratio and the Eye

The contrast ratio, *CR*, of a display is the ratio of the maximum display intensity to the minimum display intensity. In other terms [40],

$CR = (L_{Dmax}/L_{Dmin})$

where L_{Dmax} = the maximum display luminance and L_{Dmin} = the minimum display luminance. Extending the definition of contrast in terms of estimated retinal illuminance gives

$CR = (I_{Dmax}/I_{Dmin})$

where I_{Dmax} = the maximum estimated retinal illuminance due to the display and I_{Dmin} = the minimum estimated retinal illuminance due to the display. The values of I_{Dmax} and I_{Dmin} correspond to the estimated retinal illuminance values for displays with luminance values of L_{Dmax} and L_{Dmin} respectively.

Display Modulation Contrast and the Eye

The modulation contrast, C_M, of a display is the ratio of the difference between the maximum display intensity and the minimum display intensity divided by the sum of the minimum and maximum intensities. In other terms [40],

$C_M = (L_{Dmax} - L_{Dmin}) / (L_{Dmax} + L_{Dmin})$

where L_{Dmax} = the maximum display luminance and L_{Dmin} = the minimum display luminance. Extending the definition of contrast in terms of estimated retinal illuminance gives

$$C_M = (I_{Dmax} - I_{Dmin}) / (I_{Dmax} + I_{Dmin})$$

where I_{Dmax} = the maximum estimated retinal illuminance due to the display and I_{Dmin} = the minimum estimated retinal illuminance due to the display. In other words, the values of I_{Dmax} and I_{Dmin} correspond to the estimated retinal illuminance values of displays with luminance values of L_{Dmax} and L_{Dmin} respectively.

Stereographic Displays using VRD

As discussed previously while treating the possibility of three-dimensional imaging systems using VRD there are two cues by which the human beings perceive the real world namely the accommodation cue and the stereo cue. There is a mismatch of the information conveyed by the two cues in projection systems so that prolonged viewing can lead to some sort of psychological disorientation.

In VRD we can generate individual wavefronts for each pixel and hence it is possible to vary the curvature of individual wavefronts which determines the focal depth, so what we get is a true stereographic view.

The Virtual Retinal Display (VRD) developed at the University of Washington Human Interface Technology Lab (HIT Lab) is being modified from a fixed plane of focus display to a variable focus display.. By integrating a deformable mirror into the VRD, the wavefront of light being scanned onto the retina can be changed and various fixation planes created depending on the divergence of the light entering the eye. Previous embodiments of 3D displays allowing for natural accommodation and vergence responses include the use of a varifocal mylar mirror and the use of a liquid-crystal varifocal lens. In the former, a reflective mylar surface was deformed by air pressure using a loudspeaker behind the mylar mirror frame. A CRT screen was positioned so that the viewers saw the reflection of the CRT in the mirror at various virtual image depths. In the latter, an electrically-controllable liquid-crystal varifocal lens was synchronized with a 2-D display to provide a 3D image with a display range of –1.2 to +1.5 diopters (1/focal length in meters). Although these systems provided for a 3D volumetric image allowing for natural human eye response, they are large and cumbersome benchtop systems.

Deformable Membrane Mirror

The deformable membrane mirror is a MEMS device that is used in adaptive optics applications. The mirror is bulk micromachined and consists of a thin, circular membrane of silicon nitride coated with aluminum and suspended over an electrode. When a voltage is applied to the electrode, the mirror membrane surface deforms in a parabolic manner above the electrode. The wavefront of a beam of light hitting the mirror membrane surface can be changed by varying the voltage applied to the electrode. With no voltage applied, the mirror membrane surface remains flat. With a certain amount of voltage applied, the reflecting beam will be made more converging. By integrating the deformable mirror into the VRD scanning system, a three-dimensional picture can be created by quickly changing the scanned beam's degree of collimation entering the eye.

Optical Design

The HeNe laser beam is spatially filtered and expanded before striking the deformable mirror. When the mirror is grounded, the beam is at maximal divergence when entering the eye. Conversely when the mirror voltage is at maximum, the resultant beam is collimated when entering the eye. The beam is reflected off a scanning galvanometer and through an ocular lens to form a viewing exit pupil. A viewer putting his eye at the exit pupil would see a 1-D image at a focal plane determined by the amount of beam divergence. With no voltage on the mirror this image is located at close range; with maximum voltage on the mirror the image is at optical infinity. In this way the optical setup provides a range of focal planes from near to far which can be manipulated by changing the voltage on the mirror.

Evolution of VRD systems

The project's initial goal was to prove the viability of forming an image on the retina using a scanned laser. As a result of the work, a patent application was filed and the technology licensed to a Seattle based start up company, Micro Vision, Inc. Under terms of the agreement, Micro Vision is funding a four-year effort in the HITL to develop the technologies that will lead to a commercially viable VRD product. This development work began in November 1993.

Prototype #1

The original prototype had very low effective resolution, a small field of view, limited gray scale, and was difficult to align with the eye. One objective of the current development effort was to quickly produce a bench-mounted system with improved performance. Prototype #1 uses a directly modulated red laser diode at a wave length of 635 nanometers as the light source. The required horizontal scanning rate of 73,728 Hertz could not be accomplished with a simple galvanometer or similar commercially available moving mirror scanner. The use of a rotating polygon was deemed impractical because of the polygon size and rotational velocity required. It was thus decided to perform the horizontal scan with an acousto-optical scanner. The vertical scanning rate of 72 Hertz is within the range of commercially available moving mirrors and is accomplished with a galvanometer.

The use of the acousto-optical scanner comes with a number of drawbacks:

* It requires optics to shape the input beam for deflection and then additional optics to reform the output beam to the desired shape.

* It requires complex drive electronics that operate at frequencies between 1.2 GHz and 1.8 GHz.

* Its total scan angle is 4 degrees. Thus, additional optics are needed to increase the angle to the desired field-of-view. Due to the optical invariant, this optical increase in angle comes with the penalty of decreased beam diameter which leads to a small exit pupil. The small exit pupil necessitates precise alignment with the eye for an image to be visible.

* It is expensive and will not, in the foreseeable future, allow the producers to reach the cost goals for a complete VRD system.

Prototype #2

To overcome the limitations of the acousto-optical scanner, HITL engineers have developed a miniature mechanical resonant scanner. This scanner, in conjunction with a conventional galvanometer, provides both horizontal and vertical scanning with large scan angles, in a compact package. The estimated recurring cost of this scanner will allow the VRD system to be priced competitively with other displays. Prototype #2 of the VRD uses the mechanical resonant scanner.. The system was built and demonstrated during the summer of 1994. The VGA resolution images produced are sharp and spatially stable.

The mechanical resonant scanner is used in conjunction with a conventional galvanometer in a combination which allows for an increase in the optical scan angle. When the mirrors of the two scanners are arranged in such a manner that a light beam undergoes multiple reflections off the mirrors, then the optical scan is multiplied by the number of reflections off that mirror. Optical scan multiplication factors of 2X, 3X and 4X have been realized. Prototype #2 uses a system with 2X scan multiplication in the horizontal axis.

Prototype #3

The third prototype system developed uses the same scanning hardware as Prototype #2 but uses three light sources to produce a full color image. In addition the eyepiece optics have been modified to allow for see through operation. In the see through mode the image produced by the VRD is overlaid on the external world.

Present Scenario

In the current version, a wireless computer with a touch-pad control is worn on the belt. Such units are largely used by the production units of many industries, most of them automobile manufacturers. Like a high-tech monocle, a clear, flat window angled in front of the technician's eye reflects scanned laser light to the eye. That lets the user view automobile diagnostics, as well as repair, service, and assembly instructions superimposed onto the field of vision. The information that the device displays comes from an automaker's service-information Web site through a computer running Microsoft Windows Server 2003 in the dealership or repair shop. The data gets to the display via an ordinary IEEE 802.11b Wi-Fi network, and all the technicians in the service center are able to access different information simultaneously from one server.

Typical MEMS scanner today measures about 5 mm across, with a 1.5-mm-diameter scan mirror capable of motion on two scan axes simultaneously Using MEMS allows us to integrate the scanner, coil windings, and angle-sensor functions all on one chip. Such a scanner provides SVGA (800-by-600) equivalent resolution at a 60-hertz refresh rate and is now in production and in products. In addition, multiple scanners could provide higher-resolution images by each providing full detail in a tiled subarea. Eventually, costs will become low enough to make this practical, allowing the scanned-beam approach to surpass the equivalent pixel count of any other display technology.

With green laser diodes, it will be possible to build bright, full-color see-through displays . Microvision uses laser light sources in many of its see-through products because our customers' applications demand display performances with color-gamut and brightness levels far exceeding the capabilities of flat panel displays, notebook displays, and even higher-end desktop displays. For today's commercial products, only red laser diodes are small enough, efficient enough, and cheap enough to use in such see-through mobile devices as Nomad. Blue and green diode-pumped solid-state lasers are still too expensive for bright, full-color, head-up or projection displays for mainstream markets, but that could change soon. In the mid-1990s Shuji Nakamura of Nichia Chemical Industries Ltd. (now Nichia Corp., Tokushima, Japan) demonstrated efficient blue and green LEDs, and then blue laser diodes made of gallium nitride. When these designs and materials are extended to green laser diodes, it will be possible to build bright, full-color see-through displays.

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As an alternative, small green laser are now being produced which use a crystal to frequency double a neodymium YAG laser. These devices are larger than desired and are not directly modulatable at the required frequency. They do however, offer a short term solution. In the HITL researchers are investigating a number of alternatives to blue and green laser diodes. One frequency doubling technique being researched uses rare earth doped fibers as the doubling medium. A second technique uses wave guides placed in a lithium niobate substrate for the doubling.

The above methods all utilize a laser as the light source. Additional work is directed at using non-lazing, light-emitting diodes (LEDs) as the light source. In order for this to be successful two primary issues are being addressed. The first issue is how to focus the LED output to the desired spot size. The second issue is the development of fabrication techniques that will allow us to directly modulate the LEDs at the desired frequency.

Enter the edge-emitting LED. Unlike conventional LEDs, which emit light from the surface of the chip, an edge-emitting LED has a sandwich-like physical structure similar to that of an injection-laser diode, but it operates below the lasing threshold. These LEDs emit incoherent beams of light that, while not so fine as a laser's beam, provide a tenfold increase in brightness. We also use multiple inexpensive surface-emitting LEDs, each contributing a portion of the overall power, to achieve high brightness. Further performance improvements of LED materials driven by huge investments aimed at general lighting applications will increase the brightness and range of applications for scanned-beam displays based on green and blue gallium nitride devices and aluminum gallium indium phosphide red LEDs.

In addition to displaying images, the scanned-beam technology can capture them. In a display, the data channel through a digital-to-analog converter controls the light source to paint a picture on a blank canvas. In image capture, the light source is steadily on, and the data channel looks at the reflections from the object through an analog-to-digital converter connected to a photodiode. The light source, beam optics, and scanner are essentially the same in both applications

Laser safety analysis

Maximum Permissible Exposures (MPE) have been calculated for the VRD in both normal viewing and possible failure modes. The MPE power levels are compared to the measured power that enters the eye while viewing images with the VRD. The power levels indicate that the VRD is safe in normal operating mode and failure modes.

The scanned beam is passed through a lens system which forms an exit pupil about which the scanned beam pivots. The user places themselves such that their pupil is positioned at the exit pupil of the system. This is called a Maxwellian view optical system. The lens of the eye focuses the light beam on the retina, forming a pixel image.

The following figure (fig.10) compares the illumination of the retina by a pixel-based display versus the VRD. Inset figures show schematized light intensity over any given retinal area in the image. Typical pixel-based displays such as CRTs have persistence of light emission over the frame refresh cycle, whereas the VRD illuminates in brief exposures.

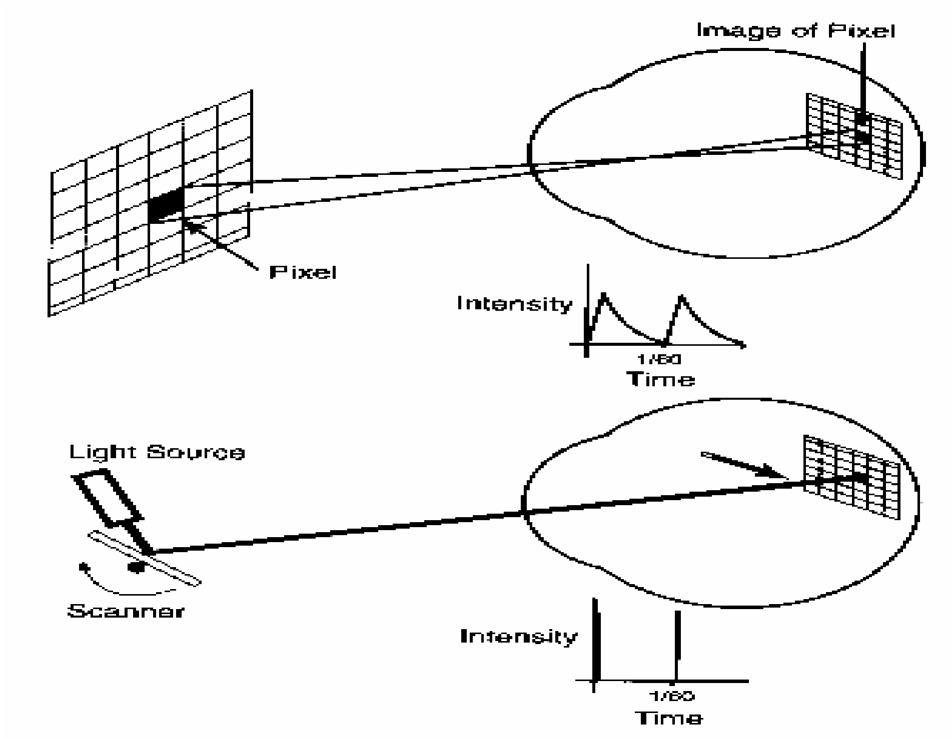

Figure.12

Preliminary tests and calculations of VRD images demonstrated that the system's power output with typical images is below the maximum permissible exposure (MPE) limits established for various lighting schemes. Measures of power output with typical images indicate that the VRD generates power on the order of 200 nanowatts during normal operation. This is below the Class 1 laser power limit of 400 nanowatts. If failure were to occur, i.e. if scanning were to stop in one or both dimensions, the power limits indicate the mechanism is still safe. To use the VRD in brighter light conditions, such as ambient daylight, higher power levels will be needed.

The power of the lasers in the VRD are just a few hundred nanowatts, and it is calculated that at these powers, the laser would need to continuously illuminate a single spot in the retina continuously for eight hours before any damage occurred and that never happens in this case.

The tests were undertaken for various prototypes assuming the laser source to be of pulsed nature, continuous wave source or as extended sources. Following the method of the ANSI standard Z136.1 (1993), researchers performed a worst case analysis for laser exposure in the visible range, which is in the 400 to 550 nanometer wavelength region. For wavelengths from 550 to 700 nm, the MPE value calculated for the 400 to 550 nm wavelength region is multiplied by a correction factor C_B which is greater than one. An 8 hour exposure was assumed based on a working day for a user who would be wearing and viewing the display continuously.

Applications of Virtual Retinal Display

Application industries for the VRD range from medicine to manufacturing, from communications to traditional virtual reality helmet mounted displays (HMD's). The VRD provides high luminance and high resolution and can also be configured as see-through or inclusive (non-see-through), head mounted or hand held, making it adaptable to a number of applications. Some specific applications in the aforementioned industries are described in subsequent sections.

Radiology

One examination performed by radiologists is the fluoroscopic examination. During a fluoroscopic examination, the radiologist observes the patient with real-time video x-rays. The radiologist must continually adjust the patient and the examination table until the patient is in a desired position. When the patient is in a desired position, the radiologist takes a film copy of the x-ray image. The positioning process can be difficult and cumbersome because the radiologist must visually keep track of a patient, a video monitor, and an examination table simultaneously. Because the VRD can operate in a see-through mode at high luminance levels, it is an ideal display to replace the bulky video monitor in a fluoroscopic examining room. The radiologist could see through the x-ray display and see the patient as well. Other features such as a display luminance control or on/off switch could easily be included for this application.

Surgery

Surgery to remove a cancerous growth requires knowledge of the growth's location. Computed tomographic or magnetic resonant images can locate a tumor inside a patient. A high luminance see-through display, such as the VRD, in conjunction with head tracking, could indicate visually where a tumor lies in the body cavity. In the case that a tumor lies hidden behind, say, an organ, the tumor location and a depth indicator could be visually laid over the obstructing organ. An application in surgery for any display would clearly require accurate and reliable head tracking.

Manufacturing

The same characteristics that make the VRD suitable for medical applications, high luminance and high resolution, make it also very suitable for a manufacturing environment. In similar fashion to a surgery, a factory worker can use a high luminance display, in conjunction with head tracking, to obtain visual information on part or placement locations. Drawings and blueprints could also be more easily brought to a factory floor if done electronically to a Virtual Retinal Display (with the option of see-through mode). Operator interface terminals on factory floors relay information about machines and processes to workers and engineers. Thermocouple temperatures, alarms, and valve positions are just a few examples of the kind of information displayed on operator interface terminals. Eyeglass type see-through Virtual Retinal Displays could replace operator interface terminals. A high luminance eyeglass display would make the factory workers and engineers more mobile on the factory floor as they could be independent of the interface terminal location.

Communications

The compact and light weight nature of the mechanical resonant scanner (MRS) make an MRS based VRD an excellent display for personal communication. A hand held monochrome VRD could serve as a personal video pager or as a video FAX device. The display could potentially couple to a telephone. The combination of telephone services and video capability would constitute a full service personal communication device.

Virtual Reality

The traditional helmet display is an integral part of virtual reality today. The VRD will be adapted for this application. It can then be used for educational and architectural applications in virtual reality as well as long distance virtual conference communications. Indeed it can be utilized in all applications of virtual reality. The theoretical limits of the display, which are essentially the limits of the eye, make it a promising technology for the future in virtual reality HMD's.

Military

Helicopter pilots require information to support time-critical (and often life-and-death) decisions. If that information is presented in a graphical and intuitive fashion, it reduces the pilot's workload and can enhance visibility in degraded conditions. A helmet-mounted display capable of presenting full-color graphical information in both day and night flight operations has been the missing link to creating an effective pilot-data interface. That ultimately could save both lives and money.

The Army has a powerful vision: the ability to overlay flight reference data, sensor imagery and weapons symbology on [images from] the outside world. Such a versatile display capability is expected to provide a significant performance boost to both aircraft and pilot. When you can also enable a pilot to see the normally invisible 'bloom' of a radar signature, or to project a 'pathway in the sky' in front of him, and to superimpose wireframe or 3-D imagery onto the terrain, it becomes even more powerful.

Army's vision of the virtual cockpit also includes a "what you see depends on where you look" concept. As the pilot looks up and out of the cockpit, various types of targeting, navigational or terrain overlays would appear. When pilots look in a downward direction, they may see "virtual" instruments projected onto the eye that literally replace many of the existing dials and multifunction displays that are in cockpits today.

Wearable "augmented reality" displays Incorporated into eyeglasses, goggles or helmets, VRD technology will display an image that doesn't block the user's view but will instead superimpose a high-contrast monochromatic or color image on top of it. This ability can enhance the safety, precision and productivity of professionals performing complex tasks.

The Future of VRD Technology

Future systems will be even more compact than present versions once the MEMS-based scanners are incorporated. Edge-emitting, super-luminescent light-emitting diodes (SLEDs) and miniature diode lasers under development will allow direct light modulation. In conjunction with application-specific integrated-circuit technology, these devices will permit the direct fabrication of a VRD display engine incorporating the electronics, light sources, and scanning assembly, all in a compact, hand-held, battery-operated package. The approach can also be adapted to image projection systems. The applications for VRD technology are varied—HUDs, color projections systems for entertainment or flight training simulators, etc. A key area for continued development is an image display system that can augment and enhance a person's task performance. Many challenges remain before the VRD reaches it's full potential. Chief among these is the development of the low cost blue and green light sources needed for a full color display.

The VRD systems are ideal candidates for displays in wearable computing, considering that the pervasive and ubiquitous computers have become the taste of the time.

Conclusion

Various strategic agencies have already started working with the VRD and with so much at stake, status reports on progress are not readily available. Nevertheless we can say that right now, all those engineers, fighter pilots and partially sighted people working with VRD will be struggling with different facets of the same problem.

The projects of interest in the field are to study the basic psychophysical processes of image perception from scanned lasers including resolution, contrast and color perception, to study the interaction of VRD images with images from the real world to enhance the augmented reality applications of the technology, to study VRD image perception in partially sighted users, to design VRD light scanning paradigms to optimize image resolution, contrast in low-vision subjects, and to design text, image and computer icon representations for low vision users and test speed.

If the VRD is capable of augmenting our real world with the extra information, how will our minds handle and integrate it all? Might it fundamentally change the way we comprehend information.

One day will we repeat the words of Caesar's Hawk in utter perplexity?

" Veritas, Qui est Veritas?"

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