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Retinal scanning display: light sources moving over the retina

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A retinal scanning display is a new kind of display that directly uses the retina as a projection screen. This differs from, for example, a TV which first creates an image on a screen outside the eye. Although a retinal scanning display needs no screen, the principle of creating an image is similar to that of a TV. Where the TV uses an electron beam to create (scan) a raster pattern on a screen, a retinal scanning display uses a beam of light to scan a raster pattern on the retina. The way to get from an equally illuminated raster pattern to an image is to modulate the intensity of the beam as it scans. Since the eye does not look at a physical screen, people often wonder what the image of a retinal scanning display will look like. Upon seeing the image, the general response is: 'It looks just like a normal display'. In fact it is a normal display, but one that has many advantages compared to other kind of displays, such as: possibility of high brightness, large color gamut, possibility of high-resolution and good image quality.

Introduction

A display is a device that provides visual information[1]. The best-known display is the cathode ray tube (CRT), which is widely used in televisions and computer monitors and which presents visual information on a screen. The eye's optical lens system relays the image on the CRT screen to the retina (see Figure 1).

This paper discusses personal displays that offer an image to a single eye only. This differs, for example, from the TV in the living room which can offer an image to many eyes at the same time. There

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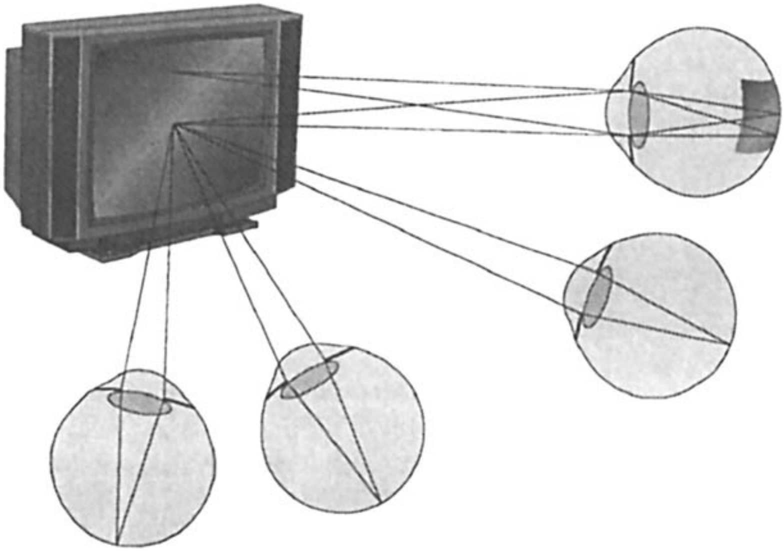

Fig. 1. The image of a TV is imaged on the retina by the optics of the eye. Since light from each picture element radiates in all directions, many eyes can view the image at the same time.

is an analogy with the more familiar difference between the speakers of an audio-set and the headphones of a walkman. A personal display, just like a headphone, is preferably head or helmet worn, low power, and light-weight. With two personal displays, one for each eye, stereoscopic vision can be created. This gives the possibility to include stereoscopic depth in the image.

Helmet (head) mounted displays

A helmet (or head) mounted display (HMD) is a personal display configured either as a binocular (two-eye) or monocular (one-eye) system. Figure 2 presents a schematic setup for a binocular HMD. A binocular display system is one that contains two separate and independently driven miniature displays. The eye-piece (located between each miniature display and the eye) projects the display image virtually at some distance from the eye, so the eye can easily focus on it. Also, the eye-piece may act as a magnifier, thereby increasing the (angular) image field.

HMDs have many different applications. For example, if the images displayed by the HMD are created by a computer and there is also a sensor on the helmet that measures the movement of the head, then the images can be updated as a function of head position. Thus, a person could look around by turning his head and perceive images

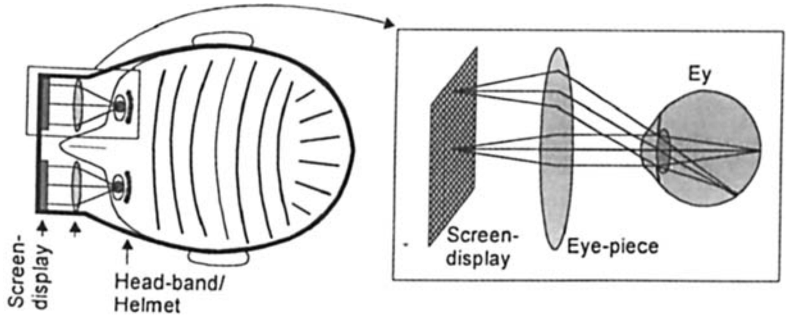

Fig. 2. A conventional HMD: miniature displays are imaged on a single eye through an eye-piece.

that make him believe he is in a virtual environment. This is called virtual reality (VR). The obvious applications of VR are training and simulations. For example, instead of flying an expensive aircraft, a pilot can practice an emergency landing in a virtual environment. Of course, improved HMD image quality means improved application realism. Other VR applications involving binocular HMDs include interactive visualization, games and psychological research. An example of psychological research is to test the driving habits of people when they enter a tunnel. If the tunnel appears as a black hole people tend to brake before they enter, causing an increased chance of accidents and traffic jams. It would be safer for a tunnel to change gradually from light to dark. To determine the optimum tunnel configuration, several tunnels could be cut in a mountain. However, it would be much cheaper and easier to flexibly change parameters, if the tunnels (and a car) would be simulated in VR.

HMDs are not restricted to applications in VR. Those who have seen the movie *'Titanic'* are familiar with the phenomena of tele-robotics. Tele-robotics uses a robot to imitate the movements of an operator, while the robot operator (wearing an HMD) sees the environment visible to the robot through two cameras located on the robot. Thus, the operator need not be physically present in a hazardous or remote environment (*e.g.* in space, in a nuclear power plant or 3,821 meters underwater).

Monocular HMDs also have many applications. For example, think about a surgeon who can click a personal display in front of his eye and quickly see a patient's condition or a motor-mechanic who can look into an image of a repair manual while working on equipment at the job site. In the field of wireless communications, a personal display could offer the possibility to view privately E-mail, faxes or any other graphical document wherever you are (see Figure 3).

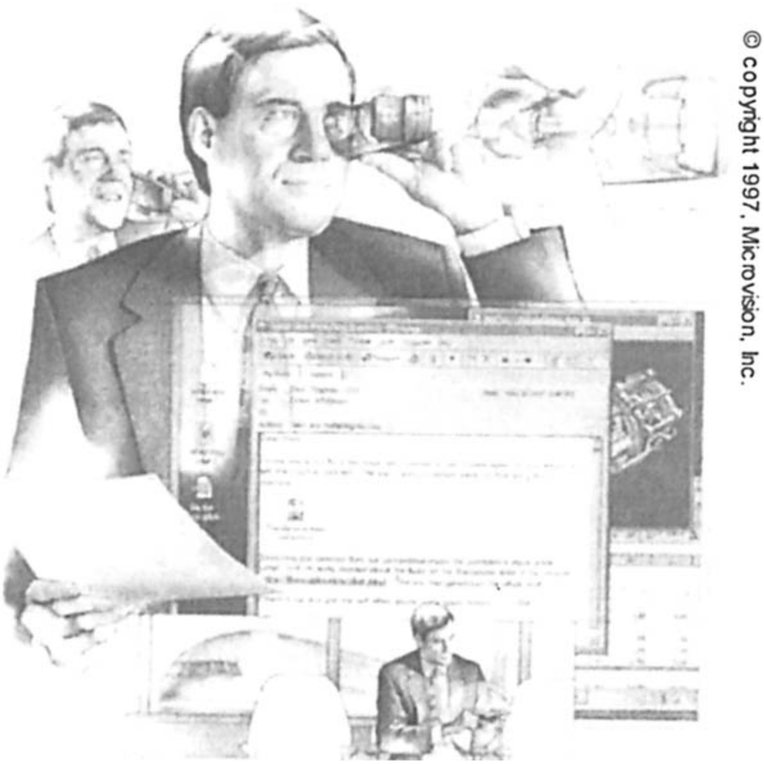

Fig. 3. An example of a personal display which is not a HMD:
A cellular telephone that can show faxes and E-mails.
Image courtesy Microvision, Inc.

Until now, the discussion has assumed an HMD design that occludes (blocks out) a person's normal vision. However, it is also possible to achieve a semi-transparent display. Augmented vision or augmented reality is the term used when the displayed image overlaps (or overlays) an image of the real world. A very simple application would be to add text and a pointer in the subject's field of view to guide someone through a museum.

Incorporating an eye tracker into an HMD design increases the number of potential applications. For example, in an occluded HMD, the eye tracker could function as a computer mouse. The viewer could simply look at part of an image, then 'click' on it – perhaps by blinking the eye. This way of working is faster and more intuitive than with the regular mouse[2]. Furthermore, disabled people could benefit from using their eyes to communicate with a computer. Finally, in applications involving an augmented HMD image, the eye tracker could be used to point at objects in the outside world. For example, in the museum example cited above, the viewer might like to know more about a specific painting. This could be done simply by looking at the painting, then enabling the display of textual information by a wink of the eye. This can only be accomplished when an image of the outside world is also captured.

The rest of this paper will discuss a kind of HMD display called a retinal scanning display (RSD), shown schematically in Figure 4. While a CRT or LCD (liquid crystal display) builds images on a screen, an RSD builds images directly on the retina. This is achieved by imaging a point source on the retina and making this point source move in a raster pattern over the retina. The intensity of the source is modulated to give each picture element (pixel) the right amount of light. If the created retinal image is repeated fast enough, the integrating properties of the visual system make the image to look flicker-free.

The history of retinal scanning displays

In the 1980s, Webb *et al.* developed the scanning laser ophthalamoscope (SLO)[3,4]. This device can be regarded as the predecessor of the RSD, even though their applications differ. The RSD projects an image onto the retina; the SLO gathers an image of the retina.

Figure 5 shows the principle of operation of an SLO. First, a beam of light is deflected by scanner S_1. This scanner is shown as a polygon whose rotation causes the light to be deflected in different directions. By means of some optics, called pupil relay 1, the fan of beams created by scanner S_1 is imaged onto a second scanner, S_2, which scans in a perpendicular direction. Now, the two-dimensional fan of beams is imaged onto the eye pupil to make sure all the light enters

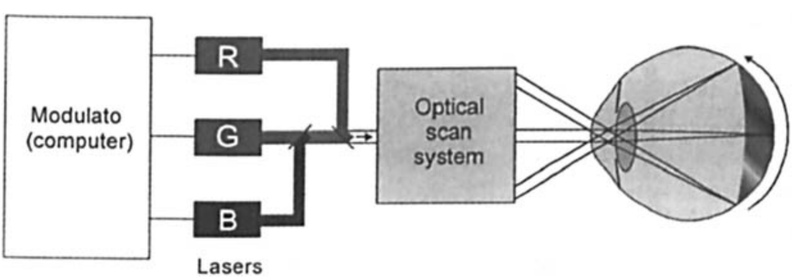

Fig. 4. *Schematic representation of a retinal scanning display. The light beams of the Red (R), green (G), and blue (B) lasers are superimposed, optically scanned (deflected in different directions), imaged onto the eye, and focused onto the retina.*

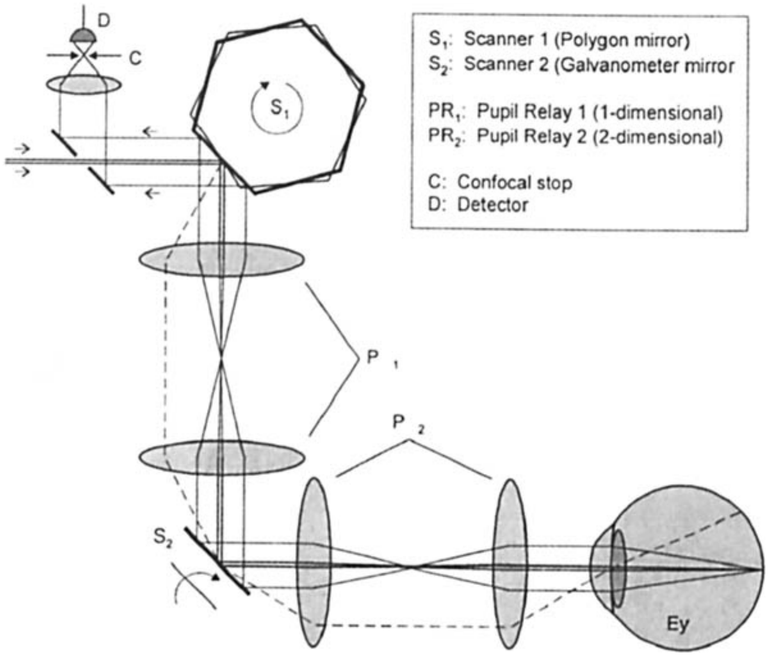

Fig. 5. Schematic setup of a scanning laser ophthalmoscope.

the eye and is guided to the retina where the beams will be in focus. To create a raster image on the retina, the first scanner must travel much faster than the second scanner. Thus, the first scanner produces horizontal lines whilst the second scanner, moving vertically, completes the projection of the raster. If the light source is not modulated in intensity, an equally illuminated raster pattern is created on the retina. Depending on the structure of the retina (bloodvessels, receptors, blind spot) where the beam is focused, more or less light will be reflected from the eye. Detector D, which captures this reflected light, is connected to a monitor to show the image of the retina in real time.

The basic principles of an SLO are very similar to the basic principles of an RSD. However, the major difference between the two devices involves the modulation of the beam intensity. Also, the whole detection scheme (for light reflected from the eye) is rendered unnecessary, which, in principle, makes the design simpler. Webb demonstrated the imaging (display) capabilities of the SLO as early as 1982[5]. Even though the basic principles of the SLO and the RSD are similar, the two systems are designed to meet completely different challenges. For example, an RSD system emphasizes reduced size and weight because of its use in HMDs.

In 1991, Sony described a display called a 'direct viewing picture image display apparatus' which is analogous to the RSD discussed in this paper. Sony's design showed that if the two scanners are positioned close together, then the first pupil relay (PR_1 in Figure 5) could be skipped. Also, they noted that, in an RSD, depth information could be added by changing the virtual image distance of each pixel separately.

Since 1992, scientists at the Human Interface Technology Laboratory (HITL) at the University of Washington and at Microvision, Inc. in Seattle have been working on an RSD called the Virtual Retinal Display™ (VRD™)[6–8]. Besides researching the related technologies, Microvision is also developing products based on their patented scanners. Presently, the military is the main customer for VRD technology. However, as the technology advances, prices will drop and the VRD will be available for the medical and for consumer markets.

The Optics Group at the Delft University of Technology in the Netherlands is also researching an RSD. Work started in 1993 with a project called 'Design and realization of an optical system for Virtual Reality'. This project ended successfully in 1997 with a table-top RSD[9]. The Optics Group continues to work on the RSD, which is now part of a large, multi-department project called 'Ubiquitous Communication'[10].

Advantages and disadvantages of an RSD

Why is it worthwhile investigating this new kind of display? Table 1 lists the advantages an RSD has compared to more conventional 'screen'-displays such as a CRT or an LCD. Presently, the RSD has two significant disadvantages. First, there are no commercially available blue or green laser diodes yet to support the development of a compact, full-color display system. This is a disadvantage because laser diodes are small and light-weight and can be directly modulated with a bandwidth that is large enough to provide necessary image resolution. Since laser diodes with a wavelength shorter than red (such as green and blue) are attractive for data storage, much research is being done, and green and blue laser diodes are to be expected in the near future[11]. Meanwhile, other kinds of lasers can provide green and blue color, but they must be modulated externally (for example, with an acousto-optic modulator). Since these lasers are too bulky and heavy to integrate in an HMD, they must be remotely positioned and the laser light guided through a fiber to the HMD[12]. In fact, being able to guide light through a fiber to an RSD

Table 1. Advantages of a retinal scanning display.

Advantage	Explanation
Higher resolution possible (1)	In a 'screen'-display, image resolution is limited by the physical size of a picture element and by aberrations in the optical system. In principle, an RSD projects an image onto the retina and not onto an intermediate screen, so resolution is only limited by the radiating area of the source and by aberrations in the optical system. With the use of lasers as a light source the effective radiating area becomes minimal (*i.e.* diffraction limited).
Higher resolution possible (2)	In a color 'screen'-display, the three different color-dots (red, green, and blue) for one pixel are often located spatially next to each other. In an RSD, on the other hand, the three different color-dots can be spatially superimposed, increasing resolution by a factor of 3.
High brightness	With lasers as light sources, an RSD can be made bright enough to provide a good, visible image even in full day-light.
Large color range	Lasers provide very pure primary colors (small wavelength spectrum). This enables the RSD to cover a large range of possible colors which the human eye is able to discern.
Good image quality over a wide image field	A 'screen'-display usually has a rather flat screen on which the image appears. In an RSD, the virtual image field is spherically curved as is shown in Figure 6. By using spherically curved mirrors to image this virtual image field onto the retina, an RSD gains the advantage of having symmetry in the system. Coupled with an appropriate optical design this symmetry may result in good image quality over a wide image field.
Pixel-by-pixel means greater image realism	Accommodation (*i.e.* the virtual distance of a pixel) means having picture elements that appear to be at different distances. This increases the realism of the image. In an RSD, the state of accommodation can theoretically be changed pixel-by-pixel by changing the vergence properties of the beam before it is launched into the scanning system. To achieve this for every pixel, the modulation bandwidth should be very high, on the order of 5 Mhz or more.

positioned on the head is much easier than guiding image information through copper wires (as is the case with CRTs or LCDs) because fibers have a very high bandwidth and they are immune to electromagnetic interference.

The RSD's second disadvantage is associated with the horizontal scanner. This scanner should be able to scan 15,750 or more lines per second for common image resolutions and its total scan angle should be large enough to display the whole resolution. As will be discussed

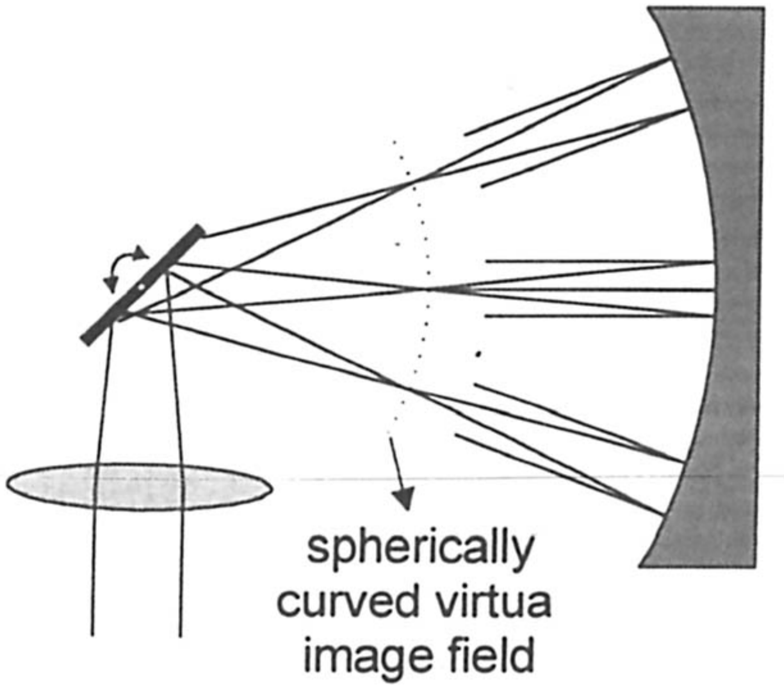

Fig. 6. A scanning system gives a spherically curved virtual image field (the surface where the beam is in focus). With a spherically curved mirror the beam can be imaged independent from the scan-direction.

below, these requirements result in scan mirrors with a relatively small surface area. This, in turn, results in a small 'exit pupil' (see Figure 7). Figure 7 also shows that a small exit pupil may result in a loss of the image on the retina when the eye rotates or translates too far. This effect is also apparent when using a microscope or a pair of binoculars, two devices which often have a small exit pupil. Thus, because the scan mirror is small, there might be a need for an additional optical system to enlarge the exit pupil. This can either be done passively (*e.g.* with a diffuser at the virtual image plane[13]) or actively, by detecting the position of the eye and adjusting the small exit pupil in space so it always stays inside the eye pupil. The latter method requires an eye tracker to be present. This, in turn, is also a very useful addition to an HMD. Using active exit pupil expansion has another advantage: the optical system can be relatively simple because optical aberrations depend on the size of the exit pupil[14].

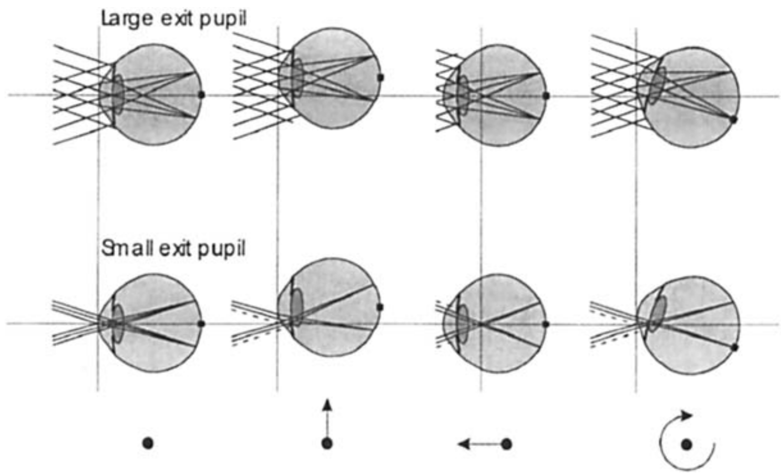

Fig. 7. The exit pupil is the position where all the beams come together. In the top row the exit pupil is larger than the eye pupil, and in the lower row the exit pupil is smaller than the eye pupil. The arrow indicates a movement of the eye compared to the left situation and the square always marks the same position on the retina. It shows that with a small exit pupil the eye has less freedom of movement.

Light sources and laser safety

At first, using a laser to project an image on the retina seems a bit strange, because lasers are usually considered dangerous devices for the eye. However, the intensity of a laser, just like any other light source, can easily be reduced by attenuators such as neutral density filters or polarization filters. Lasers are ideal as light sources in an RSD because they can effectively function as point sources, giving them the ability to make picture elements of minimum size. An incandescent lamp or even a normal light emitting diode (LED) has a much larger radiating surface. In fact, these light sources often produce much more light than a laser, but their energy is not as concentrated. Since LEDs are now available in green and blue while laser diodes are not, Microvision is investigating new kinds of green and blue LEDs that radiate light from a smaller surface.

The difference between RSD imaging (on the retina) and normal imaging (like the projection of this text on your retina) is this: with an RSD, a picture element is illuminated with very short pulses (typically 100 ns or less) while a picture element of this text is continuously present on your retina. Because the visual system can be considered as an energy integrating device (in first approximation), the energy of the pulses in an RSD should be relatively high to compensate for the dead time a picture element is not illuminated. Note that in a CRT the picture elements are also pulsing in intensity. However, the relatively long decay time of the phosphors on the screen causes the pulse time to be relatively long.

ANSI standards governing the safe use of lasers[15] do not discuss scanning a beam in the eye. However, published analyses[16,17] typically utilize conservative models for scanning a light beam in the eye to evaluate the safety aspects of the RSD. These papers find that for a display with normal luminance (100 cd/m^2) an RSD is not expected to be hazardous.

The scanners and resolution

In an RSD, the scanners are the heart of the system. As shown in Figure 5, the scanners deflect the light in different directions which will cause the image of the light source to move over the retina. To avoid image flickering when the light source is moving over the retina, scanning must occur at a very high speed. Experience with television and computer monitors indicate an image should be refreshed every 1/60th of a second (or less) to avoid flickering. Research at the University of Washington, on the other hand, indicates that the human eye/brain is slightly less sensitive to image flicker with an RSD[18]. However, if an RSD is used as a peripheral device for a standard computer, it should comply with the scan-rates of the video board. For example, if the video board produces a signal at VGA resolution (640 $\times$ 480 pixels, refresh rate of 60 Hz), then the scanner generating the horizontal lines must be able to scan 31,500 lines per second. Accordingly, the RSD's vertical scanner must be able to scan at a rate of 60 Hz.

The scanners' speed, size, and scan angle are all important. First, size (and weight) are important when the scanner must be integrated in a light-weight, head-mounted construction. Second, the product of used mirror size and scan angle is a measure of the optical resolution that can be obtained. For example, if the beam on a scanner has a diameter of 1.2 mm and the scanner has a total optical scan angle of 48 degrees, then the maximum optical resolution becomes approximately 1,827 just-resolvable points. This number is not infinite because of diffraction: *i.e.* the image of a point source will always have a finite size (depending on the size of the optical stop; in this case, the RSD's mirror).

Because of the scanner constraints cited, Holmgren and Robinett concluded in 1993 that there were no off-the-shelf scanning technologies available that could be used as the horizontal scanner in HMD system[19]. The technologies they examined were acousto-optic deflection, rotating mirror polygon scanning, galvanometer scanning and piezoelectric deflection. Since that study, however, scanning devices have been developed that do fulfill the requirements for use in a HMD.

The Delft University of Technology uses a small, magnetically-levitated mirror polygon (see Figure 8) in their RSD. This mirror polygon, which was originally developed for an optical tape recording system[20] by Philips Research, Eindhoven, The Netherlands, is small, light-weight, and spins very fast. The polygon's position in space (three translations and two rotations) and its rotational velocity are determined by the miniature optical tower on top of the (vacuum) housing around the polygon. With a scanning speed of more than 3,150 Hz (*i.e.* 31,500 lines per second), a beam of 1.2 mm, and a useable total optical scan angle (*i.e.* the angle for which the beam will fall completely on one facet) of 48°, it was shown above that the system could achieve at least VGA resolution. The specific polygon used in the Delft RSD setup at this moment scans at a much lower frequency (15,625 lines per second) according to the PAL TV standard. The resolution of the system (768 × 576) is higher than VGA though, because the images are scanned interlaced.

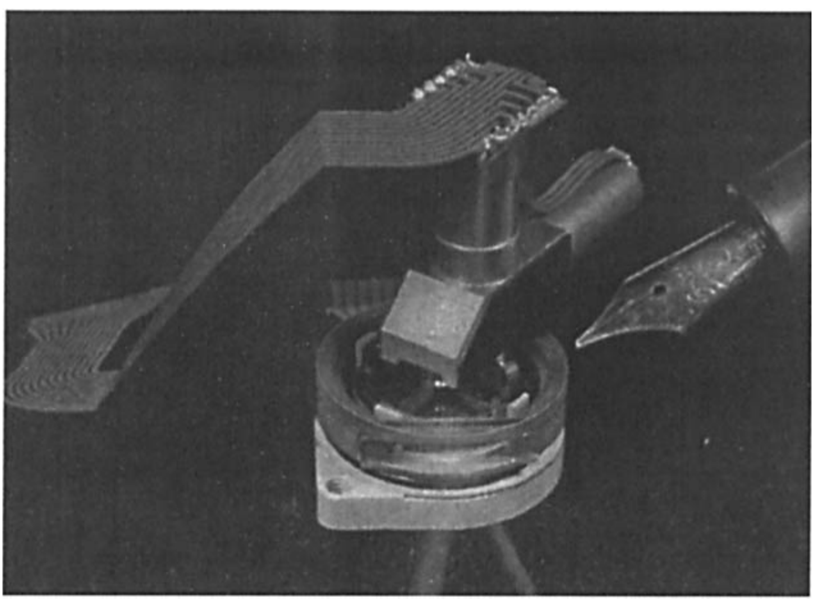

Fig. 8. *The Philips scanning polygon mirror. Image courtesy Philips Research.*

At the University of Washington and at Microvision, Inc. a mechanical resonant scanner (MRS) has been developed for use in the VRD. This scanner uses a mirror suspended on two torsion bars, and the mirror is made to resonate at its natural frequency. As shown in Figure 9, the complete scanner is very small while the scan mirror surface is still relatively large. When the mirror resonates, it scans two lines in one cycle: one line when the scanner rotates in one direction and the second line when the scanner rotates back to its original position. Of course, the image data for the line that is scanned backwards must be electronically adjusted.

Since the mirror surface is relatively large, the optical scan angle of the MRS can be doubled by using this scanner twice in the optical train[21]. A large mirror size also means that the optical resolution can be high. Microvision is therefore also working on an HMD with a resolution equivalent to high definition television (HDTV).

Microvision is also developing a micro electro mechanical system (MEMS) scanner. This is also a resonant scanner. However, the MEMS scanner is smaller than the MRS, bi-directional (one scanner moves both horizontally and vertically), and it can be made with a semiconductor-like processing method, resulting in low cost production (in volume). The first RSD display in which the MEMS scanner will probably be integrated is a mini display for a cellular phone.

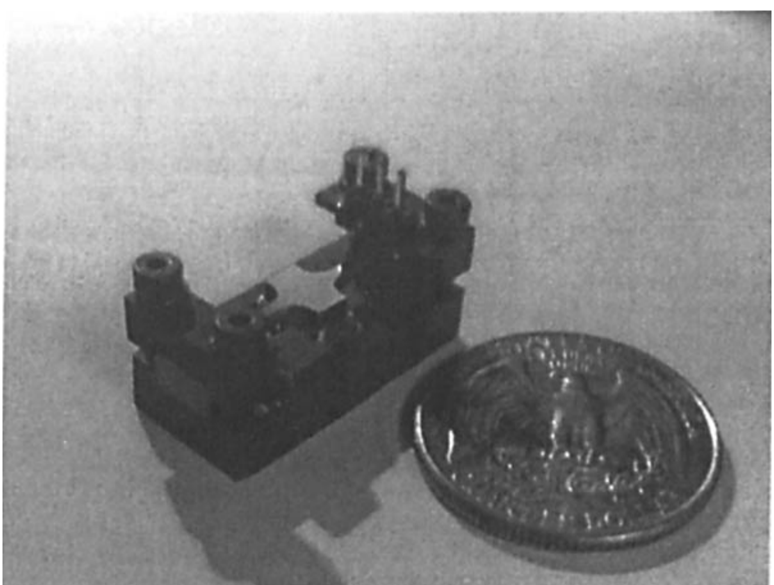

Fig. 9. Microvision's Mechanical Resonant Scanner. Image courtesy Microvision, Inc.

What's next

The basic principles of the RSD have been demonstrated. Now, more research time is needed on the visual aspects of the display and on its image quality. At the University of Washington, researchers have found that an RSD has less flicker sensitivity and gives a higher brightness response than a CRT[17,18]. While the exact reason for these results is not yet fully understood, it could involve the very short time and high brightness with which one pixel is illuminated, the high degree of color saturation, or the coherence of the light. Microvision continues to work on miniaturizing the scanners and on preparing the whole RSD system for the market. Also, research at Microvision gives more insight into the image quality of the display. A recent paper discussed the trade-offs between resolution and contrast of an RSD when looking at scan mirror size and beam clipping[22]. At the Delft University of Technology, the research on RSDs is being pursued as part of the multi-department project 'Ubiquitous Communication'[10]. This project will incorporate a wireless, see-through RSD. The emphasis in this research will probably be on eye-tracking in an RSD and on perception issues when both the outside world and the displayed image are overlapping. This work will lead to displays that bring virtual reality closer to reality.

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