

# Ultra-wide FOV Retinal Display

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## Abstract

Currently available screen and retinal head mounted displays have insufficient field of view to fully exploit many virtual and augmented reality applications. Screen based displays suffer from weight and size restrictions as the image sources, electronics, and viewing optics need to be head mounted. Retinal displays need only the scanning and optical delivery components to be head mounted, but current retinal displays suffer from a small field of view.

This paper proposes a novel, non-linear, non-paraxial optical design that enables an ultra-wide field of view display using existing small scan angle MOEMS scanners. A model of the design and estimated specifications is presented. The retinal display has an estimated  $100^{\circ}\text{H}$  by  $90^{\circ}\text{V}$  field of view at the pupil of each eye. The display will have XVGA resolution, and a 15-20mm exit aperture, and estimated 4cm eye relief.

**Keywords:** Retinal display, wide-field, scan magnification, virtual reality, augmented reality

## 1 Introduction

A retinal display works by projecting images directly into the eye and onto the retina. The image is generated sequentially by scanning a light spot in a raster pattern across the retina. Lasers and fast mechanical scanners are generally used to obtain video rate images.

Most Head Mounted Displays (HMD) use a small screen as the image source, and use viewing optics to magnify the size and angular extent of the image. However, for retinal displays, the image is considered to be virtual as there are no imaging optics to magnify a real display source.

Performances of screen based displays are limited due to practical constraints. For example, for light weight displays the screen needs to be small, and for a small screen to have good field of view it needs to be magnified or close, degrading eye-relief. Additionally, as magnification increases, resolution degrades.

Retinal displays have several advantages over screen based displays, such as; the resolution is limited only by the spot size and modulation bandwidth, both of which can be much higher than current screen technology. With no viewing optics or screens, the scanner is the only component that needs to be head mounted so the lasers and control electronics can be remote, resulting in lighter displays. High brightness and deep colour saturation can be achieved using lasers, even at high resolution.

## 2 Background

Retinal displays have their beginnings in laser scanning ophthalmoscopes that are used for imaging the retina for diagnostic purposes, Webb et al [1]. In fact, retinal displays can be adapted for use in this mode of operation to uniquely identify the user. The ideal display performance specification is to match the capabilities of the human eye. The eye is capable of an angular resolution of about 1 arc minute, and has an angular field of view of approximately  $140^{\circ}$  horizontally and  $90^{\circ}$  vertically with a  $120^{\circ}$  overlap between the eyes. This translates to an equivalent pixel resolution of  $8,400 \times 5,400$ , per eye, Tidwell [2]. For best colour saturation and a balanced white, laser or LED colours should be 650nm (red), 530nm (green), and 460nm (blue).

### 2.1 Current techniques and devices

Several companies have developed retinal displays, including Sony, Motorola, NEC and Microvision. A list of head mounted displays maintained by Bungert [3] is useful for comparing current technology and products.

Pioneering work in developing retinal displays was carried out by Furness et al [4] of the Human Interface Technology Laboratory, University of Washington. This work has been commercialised by a Seattle company, Microvision, and their consumer product is called Nomad. A selection of head mounted displays with performance details is listed in Table 1.

**Table 1:** Display performance specifications

Company	Type	Field of view	Resolution	Colour	Size	Weight	Cost
Microvision	Retinal display	23H° x 17V°	800 x 600	N, Red	small	230g	US\$4K
CAE-Electronics	CRT	80H° x 60V°	1280 x 1024	Y	large	2,240g	US\$50K
Kaiser Electro-Opt	Scanned CRT	60H° x 40V°	1280 x 1024	Y	large	800g	US\$145K
Virtual Research	AMLCD	43H° x 36V°	640 480	Y	medium	1,000g	?
General Reality	AMLCD	21H° x 18V°	800 x 600	Y	medium	400g	US\$2K
I-O Display Systems	LCD	21H° x 16V°	800 x 600	Y	small	230g	US\$1.2K
Icuiti Corp	LCD	21H° x 16V°	640 x 480	Y	small	100g	US\$0.5K

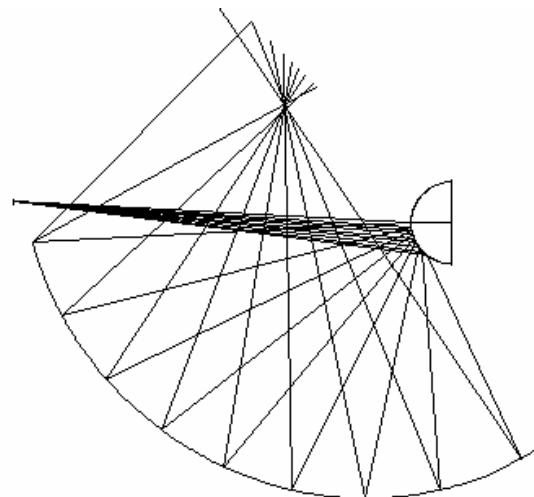
Microvision's Nomad system uses propriety Micro Resonant Scanners (MRS) that are fast (20kHz) but have a small mechanical scan angle, 3°. This scan angle is increased using multiple reflections by a factor of four. In a recent development [5] of a MRS, a bi-axial magnetic drive has pushed the mechanical scan angle up to 9°, suitable for XVGA operation, but still with relatively narrow field of view. Note, that the actual angle scanned is the optical scan angle which is twice the mechanical scan angle.

## 2.2 Performance limitations

The main problem with current retinal display technologies are the conflicting requirements of large scan angle (to achieve good field of view) and high speed scanning (adequate refresh rate). Also, the size of the beam at the pupil (exit aperture) needs to be large enough to minimise effects of eye movement. That is, if the eye moves too much the rays will not enter the eye so the image is lost. With panel displays, it is very difficult to design delivery optics that maintain etendue for a wide FOV.

## 3 Novel solution

What I propose is a non-linear, non-paraxial optic design as shown in Figure 1.

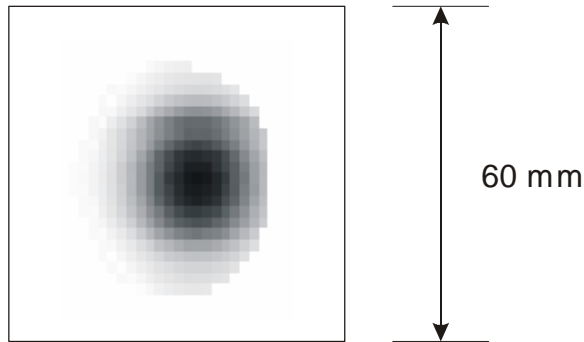


**Figure 1:** Ultra-wide FOV Retinal Display

The laser beam is scanned over a small input angle (about 4°) propagating from the left-hand side of Figure 1 to the right, reflecting off the hemisphere.

The reflection off the sphere effectively magnifies the scan angle by over a factor of twenty, diverging the ray bundle to over 110°. The ellipsoidal reflector then converges the rays to one location, where the pupil is located. The field of view at the pupil in the example given in Figure 1 is about 95°. The ellipsoid is modified to compensate for varying location of the virtual foci inside the sphere, with the fixed foci of the ellipsoid located at the pupil. Depending on the initial beam profile, the resulting spot at the pupil of the eye has a large exit aperture size of about 12mm as shown

by the greyscale irradiance plot in Figure 3. This minimises effects of eye movement.

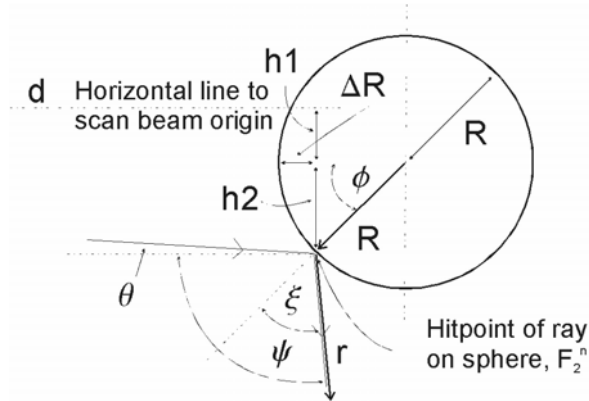


**Figure 2:** Irradiance plot of spot at pupil

Because of the magnification of the input scan angle, high speed, but small angle MOEMS type scanners can be used, and still generate a wide field of view ( $100H^\circ \times 90V^\circ$ ) at each eye. The use of all reflective optics also means that the technique is wavelength insensitive (colour), as opposed to refractive optics that can introduce chromatic aberrations in colour systems.

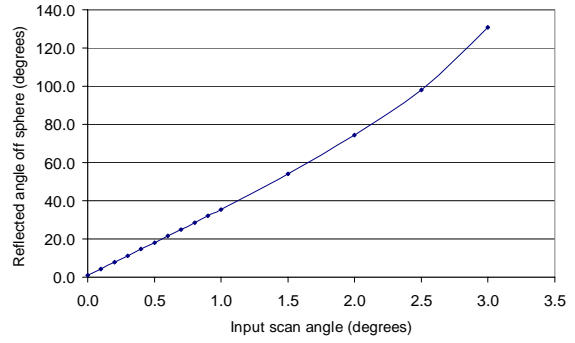
### 3.1 Non-linearities

Magnification of the input scan angle is non-linear, but surprising not highly so. I suggest that non-linearities in the system can be compensated by pre-distorting the image or scan pattern so a corrected or rectified image reaches the retina. This has in fact already been done by Schonlau [6] for a similar ellipsoidal converger. The geometry of the reflection off the sphere is shown in Figure 3.



**Figure 3:** Incident in reflected rays configuration.

The equation for the relationship between sphere angle  $\phi$  and the input angle  $\theta$  is complex, and is not shown. But, a plot of the non-linearity between the input scan angle, and the sphere angle is shown in Figure 4.



**Figure 4:** Input scan angle vs sphere angle

Although the magnification effect is not linear, for a modest input scan angle of  $3^\circ$  it is approximately so. This can be readily compensated for by pre-distorting the image. Note, that the sphere angle is not the angle seen at the eye, which is approximately double the sphere angle.

### 3.2 Lagrange Invariant

The Lagrange invariant is an important theorem in optics that states that in an optical system the product of the aperture and angular field of the system remains invariant throughout the optical system. That is, if the aperture changes in the system, the angular field inverse changes to keep the product constant. The Lagrange invariant is also known as the optical invariant or etendue. This is expressed in equation (1), where  $n$  and  $n'$  are the refractive indices before and after the optical system,  $h$  and  $h'$  the object and image transverse heights, and  $u$  and  $u'$  the angular fields, respectively.

$$n^2 a^2 \theta^2 = n'^2 a'^2 \theta'^2 \quad (1)$$

where,  $n$  and  $n'$  are the refractive indices of the medium before and after the optical system.

$a$  and  $a'$  are the apertures of the optical system.

$\theta$  and  $\theta'$  are the input and output angles.

For the proposed system,  $n = n'$  for air.

$a = 1\text{mm}$  diameter spot from the laser.

$a' = 12\text{mm}$  as modelled.

$\theta = 4^\circ$ , and  $\theta' = 95^\circ$ .

It can be easily seen then that equation (1) does not hold. This is because the standard definition of etendue is a paraxial quality, but the system I have described is not paraxial. A more generalised definition is given by Welford [7] as expressed in equation [2].

$$n^2 dx dy dL dM = n'^2 dx' dy' dL' dM' \quad (2)$$

where  $dx$ ,  $dy$ ,  $dx'$ , and  $dy'$  are incremental displacements of the ray object and image points.

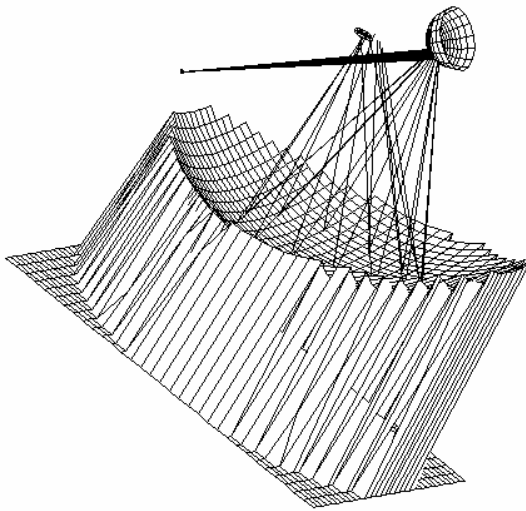
$dL$ ,  $dM$ ,  $dL'$ ,  $dM'$  are the directional cosines of the corresponding rays to be traced through the system.

In this case we get a much better agreement as illustrated in equation (3).

$$\begin{aligned} (1\text{mm})^2 (\cos 4^\circ)^2 &= 1.00 \\ (12\text{mm})^2 (\cos 95^\circ)^2 &= 1.09 \end{aligned} \quad (3)$$

#### 4 3D Model

The design has been extended to 3D as can be seen in Figure 5.



**Figure 5:** 3D plot of optics for small cone angle

Note that the convergence of the cone of rays shown in Figure 5 is not exact. This is due to a lack of accuracy in the calculated ellipsoid, which is computationally intensive. Optimisation of the algorithm and faster computing resources will enable highly accurate generation of the ellipsoid.

#### 5 Applications

There are numerous HMD's on the market, and companies have come and gone with the latest and greatest in displays. But, as can be seen in Table 1 most displays do not have a wide field of view. The high end military displays are still some way from the ideal, matching the human eye. The CRT displays are good quality, but are very heavy and expensive.

There is a 'magic' 80 degrees field of view, over which the user perceives a fully immersive experience. Many virtual reality applications would benefit from a wide angle immersive display. As the ellipsoid can be made partially reflective, augmented reality applications would also benefit from such a display. In augmented reality the image exists in only a small part of the view of the real world. The capability of moving the image within the FOV of the real world view will help further with eye movements.

This ability will also open up new applications for augmented reality and enhance existing ones.

#### 6 Future

With the development of MEOMS technology and new laser and LED light sources becoming available, retinal displays will become as small and light as a pair of sunglasses. The integration of light sources with control and communications electronics, and the MOEMS scanners on a single chip will lead to mass production of the displays. This will reduce the production costs until they become a consumer product, albeit a high performance one. Recent performance advances in polymer optics will also facilitate mass production. Wireless technology will link the displays to wearable computers, enabling a new era in human/machine interface.

#### 7 Acknowledgements

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