HIGH RESOLUTION VIRTUAL DISPLAYS

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ABSTRACT

A virtual display with 1120 x 900 pixel resolution has been constructed using a high density LED array and scanning optics. The display has a field of view of 25° x 20°. The display is small, light weight, and suitable for hand-held or head-mounted use. Pixels appear red on a jet black background. Individual pixel size is 1.3 arc minutes, which is near the resolution limit of the human eye. Pixels appear crisp and sharply defined. Contrast ratio is over 500:1. The paper describes operation of the display in detail and discusses design tradeoffs encountered in the development of high resolution virtual displays. Extension of this design to other resolutions and field of views is also explored. Planned production models of the display are described.

INTRODUCTION

Reflection Technology was founded in 1987 to manufacture miniature virtual displays. The company's best known product is the Private Eye®, a head-mounted display with 280 x 720 resolution, shown in Figure 1. The Private Eye has been built into a wide range of portable information products such as an electronic maintenance manual developed by Hughes Aircraft. These products store information, retrieve it remotely and display it. Information becomes more portable without sacrificing full screen capability.

This paper describes a new version of this display, the Megapixel Private Eye. As the name implies, the display has over one million pixels with 1120 (H) x 900 (V) resolution. Screens are sharp red on a jet black background, with a contrast ratio over 500:1. The display can be held to up to the eye or mounted on a headband as shown in Figure 2. Development of the prototype Megapixel Private Eye was funded in part by Sun Microsystems Laboratories, Inc., Mountain View CA.

Figure 1: 280 x 720 Private Eye

Figure 2: 1120 x 900 Megapixel Private Eye

Partners Program

A small quantity of Megapixel Private Eyes have been produced and are available now to customers through the company's Technology Partners Program. These initial units are engineering prototypes intended to allow customers to begin evaluation and product development. In addition, Reflection Technology anticipates producing a production version for delivery in 1993. A later section of this paper discusses plans and specifications for this design.

DESCRIPTION OF MEGAPIXEL PRIVATE EYE

The Private Eye Megapixel display may be held in the hand, or head mounted. The user looks into a 32 mm x 26 mm viewing window to see the screen image. Generous eye-relief allows using the display with glasses. Focus may be adjusted with a slider knob to suit the user's preference. The screen image appears 25° wide, and 20° wide. An 8.5 by 11 inch sheet of paper has the same apparent size when viewed from a distance of two feet. Figure 3 lists the Megapixel Private Eye specifications.

RESOLUTION	1120 (H) x 900 (V)	EXIT PUPIL	16 mm x 16 mm
PIXEL SIZE	1.3 arc-minutes	EYE RELIEF	20 mm nominal
FIELD OF VIEW	25° (H) x 20° (V)	FOCUS RANGE	250 mm to ∞
BRIGHTNESS	1 footlambert	ENCLOSURE	rectangular metal box
IMAGE COLOR	660 nm Red, on black	SIZE	55 x 45 x 175 mm
REFRESH RATE	50 Hz	WEIGHT	330 grams

Figure 3: Private Eye Megapixel Specifications

Individual pixels are square, and are 1.3 arc-minutes in size. This is close to the resolution limit of the human eye, which is generally taken to be 1.0 arc minute under ideal conditions. When greatly magnified, as shown in Figure 4, pixels are sharp and well formed. The photo in Figure 4 shows a small area of the screen, highly magnified. The photo covers an area approximately 180 pixels x 120 pixels. This is 2% of the total screen area.

Theory of operation

The basic display mechanism comprises a linear array of 1120 tiny LEDs, a magnifying lens, and a scan mirror. Through the lens, the array of LEDs appears 25° wide, corresponding to a single horizontal row of pixels. The vibrating motion of the scan mirror sweeps the virtual image vertically, painting out a rectangular raster area. The LEDs are turned on/off in synchronization with the mirror motion to create the desired image [1].

DETAILS OF IMPLEMENTATION

LED array

Very high resolution LED arrays can now be made at a reasonable cost. The primary force behind this development has been the drive to replace the laser and scanning polygon in laser printers with an LED array. Many vendors are developing LED bars for printers, and as a result, technology related to the production of these arrays has advanced rapidly [2]. Arrays 0.5 meter or more in length are routinely produced for use in xerographic LED printers.

The 1120 element LED array used in the Megapixel Private Eye is built up from four 280 element LED array modules currently used in another Reflection Technology product [3]. One of these modules is shown in

Figure 5. Each module contains a single 8.4 mm long GaAsP LED die, with 280 LED emitters located on 30 micron pitch. The LEDs are actually placed in two slightly offset rows, so that no gaps between emitters are visible in the final raster image. Conventional GaAsP LED fabrication technology does not lend itself to production of matrix addressable arrays, so each LED must have its own current driver. The drivers are located on separate custom CMOS die, one on each side of the LED chip. Because of the large number of connections, two rows of wire bonding are required. In each row of wire bonds, the rows are on a 120μ pitch.

These four modules are optically combined into a 33.6 mm array by use of a beamsplitter, as shown conceptually in Figure 6. The arrays must be aligned to an accuracy of better than 5 microns if visible defects in the raster image are to be avoided [4]. This can be accomplished with appropriate fixtures to allow micrometer adjustment of the arrays, but it is a delicate task. Once the arrays are aligned, the are permanently fixed in place with epoxy adhesive. This technique is appropriate for prototype development, but is not advocated for high volume.

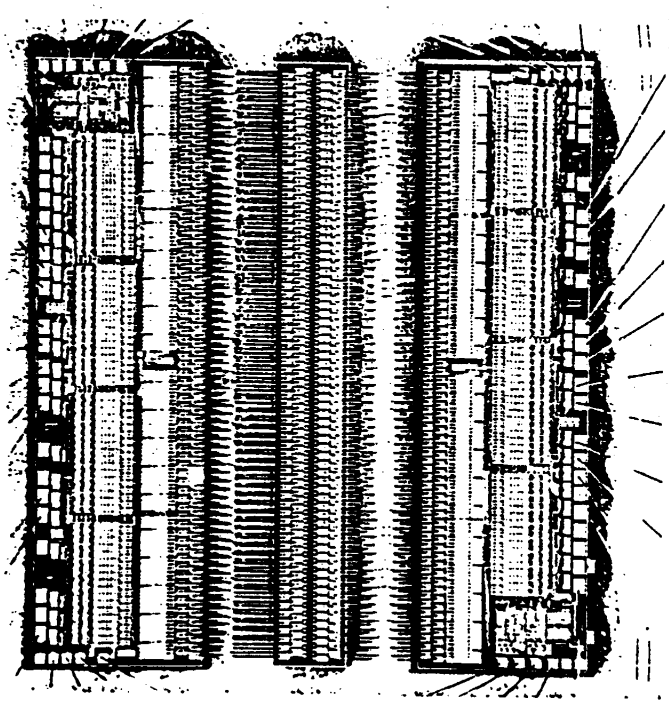

Figure 5: 280 LED array module

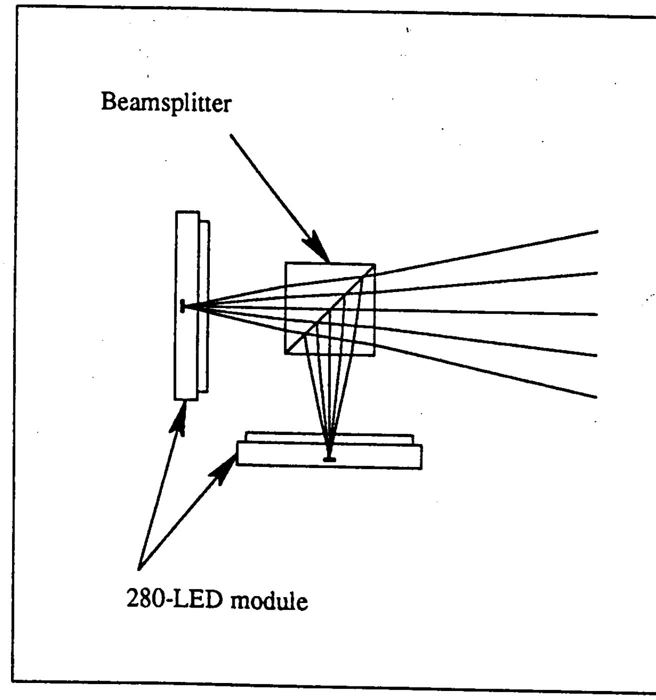

Figure 6: Optically stacking shorter arrays to create a long array.

Lens system
The optical layout of the Megapixel Private Eye is shown in Figure 7. All elements are glass. In spite of the simplicity of the layout, the complete system (including the viewer's eye) is nearly diffraction limited. The primary image defect is a slight field curvature (1/4 diopter) and a smaller amount of astigmatism (1/10 diopter). In addition, some pin-cushion distortion is present. A focus adjustment has been found important to user comfort. The focus adjustment range is 2 diopters to ∞, corresponding to moving the virtual image from a near distance of 250 mm to infinity. This is accomplished by physically moving the LED array/beamsplitter assembly with a slider knob.

The optical design is constrained by the presence of the beamsplitter, which precludes placing elements with power close to the image plane. The design shown in Figure 7 represents the best we were able to do with the beamsplitter present. However, in a production product, a single long LED array would be used, eliminating the need for a beamsplitter. Figure 8 shows a very satisfactory design that might be used with a single LED array. The horizontal FOV (field of view) has been increased from 25° to 30°. Field curvature and astigmatism are reduced to negligible values, and distortion is largely eliminated. All surfaces are spherical.

The LED light is quite narrow-band, with a bandwidth of only 20 nm and nominal wavelength of 660 nm. Surprisingly, the lens design must still take color correction into account. If this is not done, for example making all three lenses of the same material, lateral color becomes the dominant aberration!

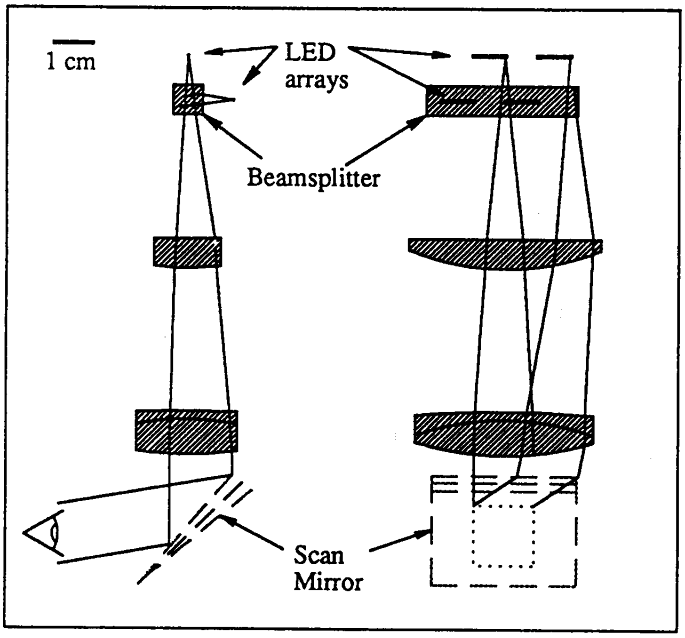

Figure 7: Optical layout of Megapixel Private Eye

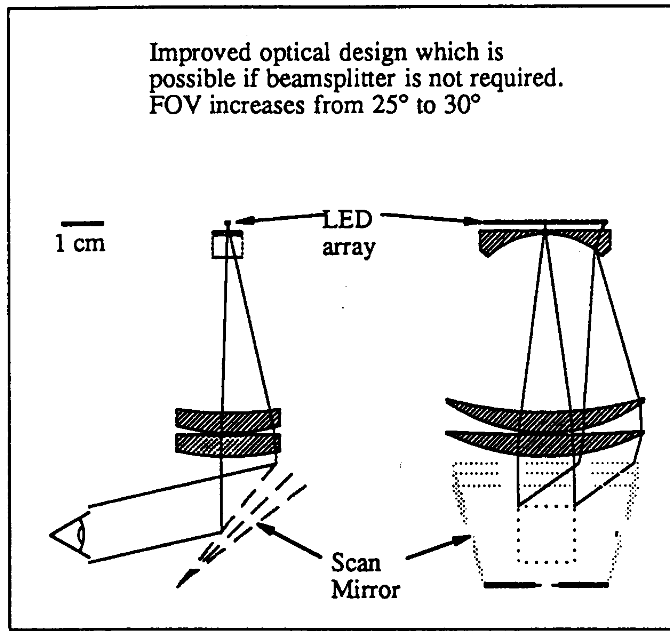

Figure 8: Improved optical layout with 30° FOV

Scan Mirror
The scan mirror is mounted on thin flexure springs, forming a high Q resonant spring-mass system. The mirror oscillation is driven at the self resonant frequency of 50 hz by a small voice coil motor. Although the tip of the mirror moves through an arc more than 8 mm long, the motor motion dissipates only about 10 mw. The magnet structure for the voice coil motor is also mounted on flexures, and tuned to have a resonant frequency matching the mirror. Together the mirror and the magnet structure form a "tuning fork" configuration, which cancels the reaction forces generated by the rapid motion of the mirror. The pivot location at the base of the mirror is somewhat unconventional. However, this somewhat subtle difference permits the use of a substantially smaller scan mirror than would be required with a conventional center pivot.

A tab on the back of the mirror moves between an IR LED and a phototransistor, and the output of the phototransistor is used to generate a sync signal. "Painting" the image is initiated by this signal. It has been found that jitter due to electrical noise in this circuit must be kept below 1.0 microsecond to avoid jitter of the image. The sync signal is also used by the mirror amplitude servo as an amplitude reference.

DESIGN TRADEOFFS

Ergonomics
Reflection Technology has found that several features seem to make a difference in the ability of a user to comfortably make use of a virtual display. While the following discussion is largely based on accumulated experience with our product, more formal research has also been conducted on this subject. [5,6].

Training
Users report that looking into a Private Eye display is comfortable and natural, although a certain amount of training and acclimatization seems to help. For example, most users eventually discover that it is not necessary to close one eye while looking at the display. This discovery considerably reduces strain when using the display for long periods. In similar fashion, most users discover that it is worthwhile to set the focus setting to the most comfortable value, even though they are physically capable of accommodating to some arbitrary focus setting.

Exit pupil
Conventional wisdom says that an exit pupil of 4-6 mm is adequate for daytime viewing, as shown in Figure 11. This may be adequate for a telescope, binoculars, or the like, where the user unconsciously "finds the pupil" while using the instrument. However, we have found that a far larger exit pupil is essential for a virtual data display. This is especially true when the display is to be head mounted, since the user has no way to compensate for slight shifts in display position. Figure 12 shows the exit pupil configuration for the

Private Eye Megapixel display. Note that the pupil is unconventional because the pupil is located at the display window, and not located some distance from the case. We have found this to be desirable, because it fosters the impression that the user is merely "looking through a window" to see a very large screen.

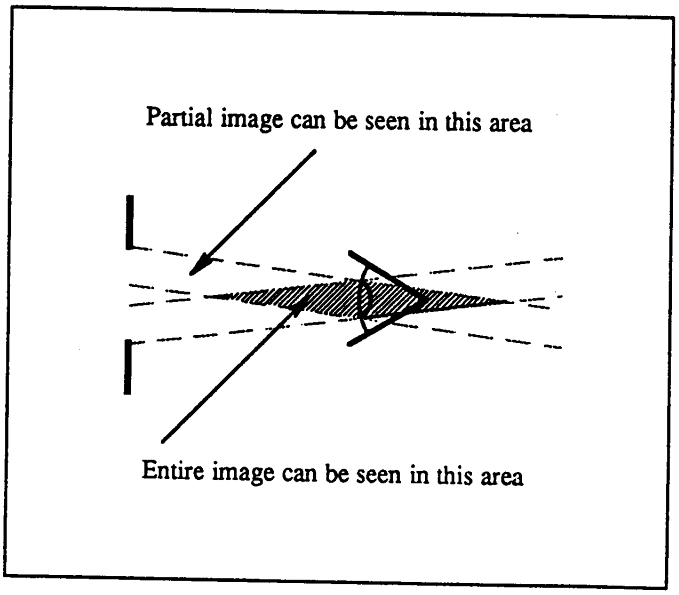

Figure 9: Conventional exit pupil

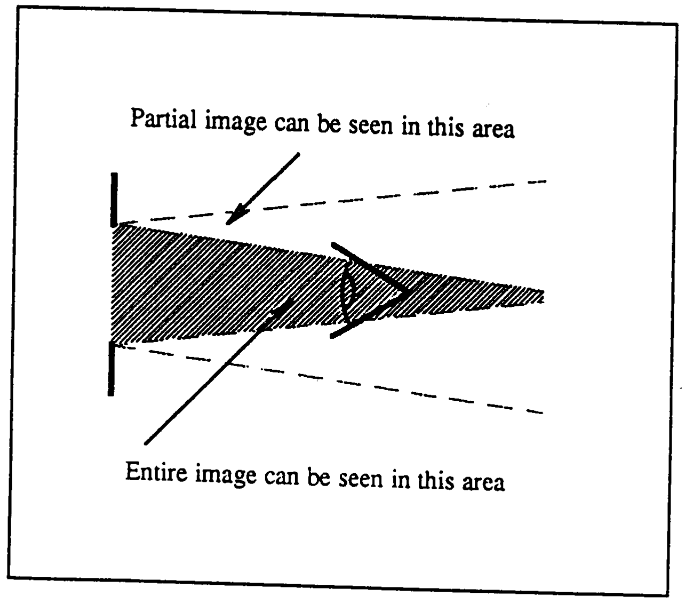

Figure 10: Megapixel Private Eye exit pupil

Image quality
In our experience, good image quality is extremely important for users to comfortably view a virtual display. Many years ago we performed experiments with a batch of poorly molded lenses, in which areas of the image were not perfectly sharp. In most cases the defect was barely visible to the naked eye, and was not detected by most users. However, instead of detecting the defect directly, users reported that the display was "hard to use" or "difficult to focus." As a result of similar experiences, we believe that good image quality is essential to ease of use.

Array density and display resolution
Resolution of a Private Eye display is ultimately limited by the size of the LED emitters. LED size in the 1120 Private Eye Megapixel display is 30 microns. Lithographic limitations limit minimum LED size to about 5-10 microns today. As a practical matter, however, minimum LED size is limited to about 15 microns by the need to connect the LEDs to the driver chips. At the present time, multiple rows of conventional wire bonds are still the highest density commercially available interconnect. Three rows of wire bonds on each side of the LED chip allow 15 micron LED pitch. Displays with resolutions up to 2K x 2K are thus possible with conventional wire bonds.

Processes under development for VLSI multi-chip modules allow higher interconnection density [7,8]. In the future, integration of GaAs LED emitters on silicon wafers will remove the need for individual off-chip bonds, and will open the door to virtual displays of 4K x 4K resolution [9].

PRODUCTION MODELS

Initial Private Eye Megapixel units are being provided to customers under our Technology Partners Program to begin work on products. Reflection Technology will study the insights and feedback gained from use of these displays in actual field conditions. Based on this input, we anticipate introducing a production version of the Megapixel Private Eye in 1993.

Handheld version
One model we expect to develop for shipment in 1993 is a handheld model, aimed specifically at high-value maintenance applications (eg, jet engine maintenance). Resolution of this version is expected to be either 1024 x 768 or 1280 x 960, depending on customer input. The production version will use a single mechanically butted array of LEDs, eliminating the weight, size, and brightness penalties caused by the beamsplitter. The display will be packaged in a smaller, more attractive enclosure. Figure 11 and Figure 12 show a mockup of the appearance of the production version. Figure 13 lists the anticipated specifications for

these production units. Figure 14 shows an optical-mechanical layout of the device.

Figure 11: Handheld version of Megapixel Private Eye Figure 12: Using production version

RESOLUTION	1024 x 768, 1280 x 960	EXIT PUPIL	16 mm x 16 mm
PIXEL SIZE	1.8, 1.4 arc-minutes	EYE RELIEF	20 mm nominal
FIELD OF VIEW	30° (H) x 22.5° (V)	FOCUS RANGE	250 mm to ∞
BRIGHTNESS	3-5 footlambert	ENCLOSURE	Sculpted plastic
IMAGE COLOR	660 nm Red, on black	SIZE	55 x 40 x 115 mm
REFRESH RATE	60 Hz	WEIGHT	150 grams

Figure 13: Specifications for Production version of Megapixel Private Eye

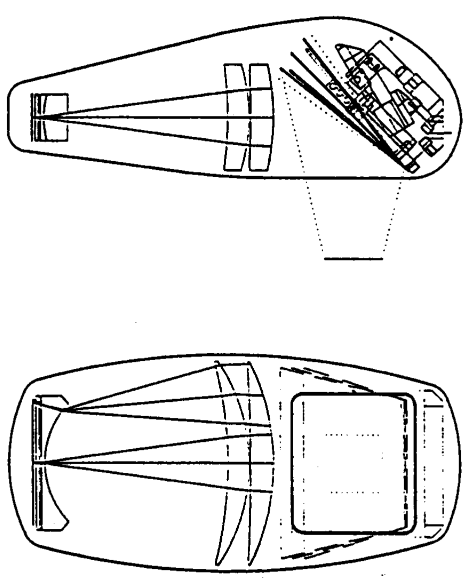

Figure 14: Optical-mechanical layout of device

See-through headmount version

It is possible to build "see-through" Private Eye displays by using dichroic scan mirrors. The scan mirrors may be counterbalanced against each other, with the necessary mechanism built into the central nose column.

See-through displays built with dichroic scanning mirrors can be quite a bit smaller than see-through displays of comparable specifications built with conventional fixed dichroic mirrors. With a fixed dichroic mirror as the final optical element, the effective eye relief after the magnifying lens increases so that the size of the lens must be quite a bit larger than the magnifying lens in the scanned system.

Figure 15 and Figure 16 show a mockup of the production version. Figure 17 lists the anticipated specifications for these production units. Figure 18 shows an optical-mechanical layout of the device.

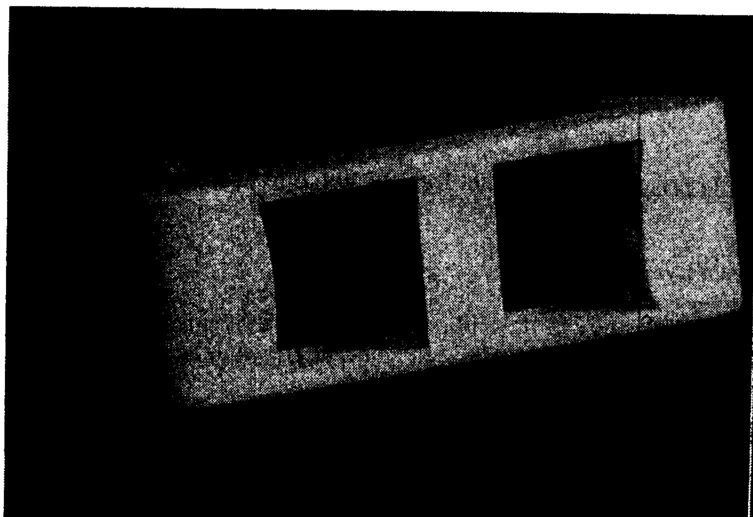

Figure 15: Mock-up of see-through Megapixel Private Eye

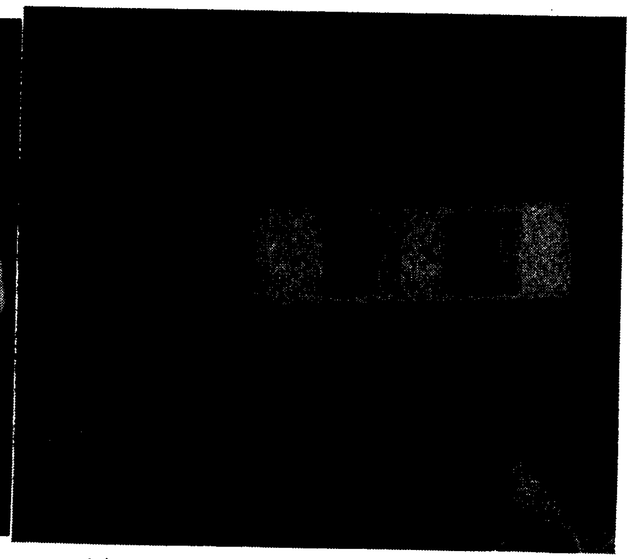

Figure 16: Using see-through version

RESOLUTION	1024 x 768, portrait mode	EXIT PUPIL	16 mm x 16 mm
PIXEL SIZE	1.8 arc-minutes	EYE RELIEF	20 mm nominal
FIELD OF VIEW	30° (H) x 22.5° (V)	FOCUS RANGE	Fixed at ∞
BRIGHTNESS	3-5 footlambert	ENCLOSURE	Sculpted plastic
IMAGE COLOR	660 nm Red, on black	SIZE	52x56x180 mm
REFRESH RATE	60 Hz	WEIGHT	150 grams

Figure 17. Specifications for see-through megapixel glasses

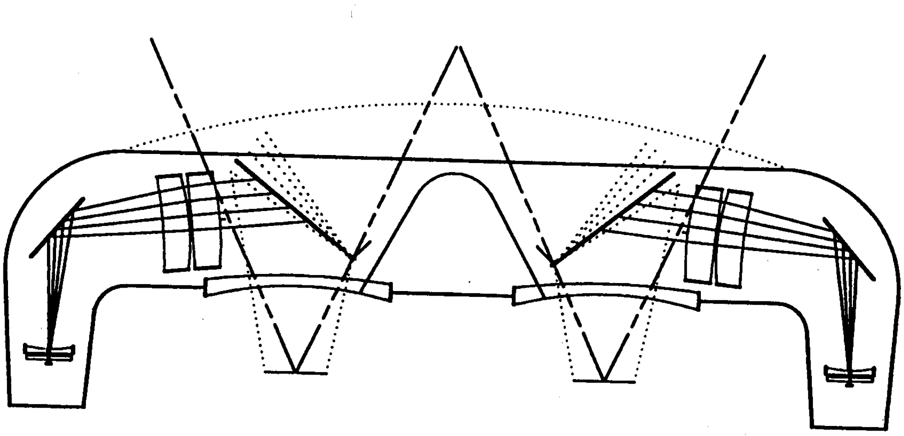

Figure 18. Optical layout of see-through headmount model

SUMMARY

Reflection Technology has developed a high resolution virtual display, which puts a million pixel image into a small package. For more information on the Megapixel Private Eye and the Technology Partners Program, contact Reflection Technology at (617)-890-5905.

ACKNOWLEDGEMENT

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Portions of this paper were previously presented at SPIE #1664, February 1992.

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[2] J. A. Finn; LED units try to gain ground on lasers; printers: Digital Review Vol. 6/6 February 1989 pp 49-50

[3] These arrays are used in the 280 x 720 "Private Eye" display.

[4] Interestingly, the arrays must be aligned very accurately in the Z dimension (along the optical axis) as well as in X and Y. If this is not done, parallax will cause the joint between adjacent arrays to be visible as the user's eye moves about within the exit pupil.

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