6

Display Devices: RSD™ (Retinal Scanning Display)

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6.1 Introduction

This chapter relates performance, safety, and utility attributes of the Retinal Scanning Display as employed in a Helmet-Mounted Pilot-Vehicle Interface, and by association, in panel-mounted HUD and HDD applications. Because RSD component technologies are advancing so rapidly, quantitative analyses and design aspects are referenced to permit a more complete description here of the first high-performance RSD System developed for helicopters.

Visual displays differ markedly in how they package light to form an image. The Retinal Scanning Display, or RSD depicted in Figure 6.1, is a relatively new optomechatronic device based initially on red, green, and blue diffraction-limited laser light sources. The laser beams are intensity modulated with video information, optically combined into a single, full-color pixel beam, then scanned into a raster pattern by a ROSE comprised of miniature oscillating mirrors, much as the deflection yoke of a cathode-ray tube (CRT) writes an electron beam onto a phosphor screen. RSDs are unlike CRTs in that conversion of electrons to photons occurs prior to beam scanning, thus eliminating the phosphor screen altogether along with its re-radiation, halation, saturation, and other brightness- and contrast-limiting factors. This means that the RSD is fundamentally different from other existing display technologies in that there is no planar emission or reflection surface — the ROSE creates an optical pupil directly. Like the CRT, an RSD may scan out spatially continuous (nonmatrix-addressed) information along each horizontal scan line, while the scan lines form discrete information samples in the vertical image dimension.

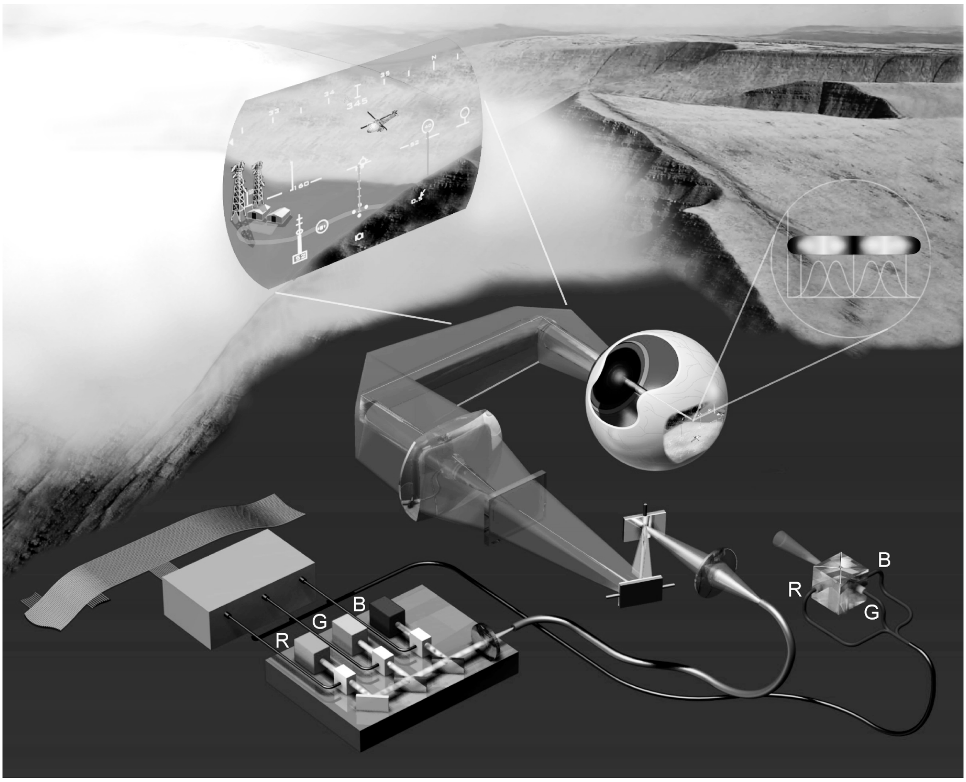

FIGURE 6.1 Functional component diagram of the RSD HMD.

6.2 An Example Avionic HMD Challenge

Consider the display engineering problem posed by Figure 6.1. An aircraft flying the contour of the earth will transit valleys as well as man-made artifacts: towers, power lines, buildings, and other aircraft. On this flight the pilot is faced with a serious visual obscurant in the form of ground fog, rendered highly opaque by glare from the sun.

The pilot's situational awareness and navigation performance are best when flying "eyes-out" the windshield, in turn requiring "eyes-out" electronic display of his own aircraft attitude and status information. Particularly under degraded visual conditions, additional imagery of obstacles (towers, the Earth, etc.) synthesized from terrain data bases and mapped into the pilot's ever-changing direction of gaze via Global Positioning System data, reduce the hazards of flight. The question has been, which technology can provide a display of adequate brightness, color, and resolution to adequately support pilotage as viewed against the harsh real-world conditions described.

For over 30 years, researchers and designers have improved the safety and effectiveness of HMDs so that mission-critical information would always be available "eyes-out" where the action is, unlike "eyes-in" traditional HDDs.[1] U.S. Army AH-64 Apache Helicopter pilots are equipped with such an HMD, enabling nap-of-the-earth navigation and combat at night with video from a visually coupled infrared imager and data computer. This particular pilot-vehicle interface has proven its reliability and effectiveness in over 1 million hours of flight and was employed with great success in the Desert Storm Campaign. Still, it lacks the luminance required for optimal grayscale display during typical daylight missions, much less the degraded conditions illustrated above.

The low luminance and contrast required for nighttime readability is relatively easy to achieve, but it is far more difficult to develop an HMD bright enough and of sufficient contrast for daylight use. The information must be displayed as a dynamic luminous transparency overlaying the real-world's complex features, colors, and motion. In order to display an image against a typical real-world daytime scene luminance of 3000 fL, the virtual display peak luminance must be about 1500 fL at the pilot's eye. And depending on the efficiency of the specific optics employed, the luminance at the display light source may need to be many times greater. The display technology that provides the best HMD solution might also provide the optimal HUD and HDD approaches.

6.3 CRTs and MFPs

Army Aviation is the U.S. military leader in deployed operational HMD systems. The Apache helicopter's monochrome green CRT Helmet Display Unit (HDU) presents pilotage FLIR (forward-looking infrared) imagery overlaid with flight symbology in a 40°(H) × 30°(V) monocular field of view (FOV). The Apache HDU was developed in the late 1970s and early 1980s using the most advanced display technology then available. The new RAH-66 Comanche Helicopter Program has expanded the display's performance requirements to include night and day operability of a monochrome green display with a binocular 52° H × 30° V FOV and at least 30° of left/right image overlap.

The Comanche's Early Operational Capability Helmet Integrated Display Sighting System (EOC HIDSS) prototype employed dual miniature CRTs. The addition of a second CRT pushed the total head-supported weight for the system above the Army's recommended safety limit. Weight could not be removed from the helmet itself without compromising safety, so even though the image quality of the dual-CRT system was good, the resulting reduction in safety margins was unacceptable.

The U.S. Army Aircrew Integrated Systems (ACIS) office initiated a program to explore alternate display technologies for use with the proven Aircrew Integrated Helmet System Program (AIHS, also known as the HGU-56/P helmet) that would meet both the Comanche's display requirements and the Army's safety requirements.

Active-matrix liquid-crystal displays (AMLCD), active-matrix electroluminescent (AMEL) displays, field-emission displays (FEDs), and organic light-emitting diodes (OLEDs) are some of the alternative technologies that have shown progress. These postage-stamp size miniature flat-panel (MFP) displays weigh only a fraction as much as the miniature CRTs they seek to replace.

AMLCD is the heir apparent to the CRT, given its improved luminance performance. Future luminance requirements will likely be even higher, and there are growing needs for greater displayable pixel counts to increase effective range resolution or FOV, and for color to improve legibility and enhance information encoding. It is not clear that AMLCD technology can keep pace with these demands.

6.4 Laser Advantages, Eye Safety

The RSD offers distinct advantages over other display technologies because image quality and color gamut are maintained at high luminances limited only by eye-safety considerations.[2,3] The light-concentrating aspect of the diffraction-limited laser beam can routinely produce source luminances that exceed that of the solar disc. Strict engineering controls, reliable safeguards, and careful certification are mandatory to minimize the risk of damage to the operator's vision.[4] Of course, these safety concerns are not limited to laser displays; any system capable of displaying extremely high luminances should be controlled, safeguarded, and certified.

Microvision's products are routinely tested and classified according to the recognized eye safety standard — the maximum permissible exposure (MPE) — for the specific display in the country of delivery. In the U.S. the applicable agency is the Center for Devices and Radiological Health (CDRH) Division of the Food and Drug Administration (FDA). The American National Standards Institute's Z136.1 reference, "The Safe Use of Lasers," provides MPE standards and the required computational procedures to assess compliance. In most of Europe the IEC 60825-1 provides the standards.

Compliance is assessed across a range of retinal exposures to the display, including single-pixel, single scan line, single video frame, 10-second, and extended-duration continuous retinal exposures. For most scanned laser displays, the worst-case exposure leading to the most conservative operational usage is found to be the extended-duration continuous display MPE. Thus, the MPE helps define laser power and scan-mirror operation-monitoring techniques implemented to ensure safe operation. Examples include shutting down the laser(s) if the active feedback signal from either scanner is interrupted and automatically attenuating the premodulated laser beam for luminance control independent of displayed contrast or grayscale.

6.5 Light Source Availability and Power Requirements

Another challenge to manufacturers of laser HMD products centers on access to efficient, low-cost lasers or diodes of appropriate collectible power (1–100 mW), suitable wavelengths (430–470, 532–580, and 607–660 nm), low video-frequency noise content (<3%), and long operating life (10,000 hr). Diodes present the most cost-effective means because they may be directly modulated up from black, while lasers are externally modulated down from maximum beam power.

Except for red, diodes still face significant development hurdles, as do blue lasers. Operational military-aviation HMDs presently require only a monochrome green, G, display which can be obtained by using a 532-nm diode-pumped solid-state (DPSS) laser with an acoustic-optic modulator (AOM). Given available AOM and optical fiber coupling efficiencies, the 1500-fL G RSD requires about 50 mW of laser beam power. Future requirements will likely include red + green, RG, and full color, RGB, display capability.

6.6 Microvision's Laser Scanning Concept

Microvision has developed a flexible component architecture for display systems (Figure 6.1). RGB video drives AOMs to impress information on Gaussian laser beams, which are combined to form full-color pixels with luminance and chromaticity determined by traditional color-management techniques. The aircraft-mounted photonics module is connected by single-mode optical fiber to the helmet, where the beam is air propagated to a lens, deflected by a pair of oscillating scanning mirrors (one horizontal and one vertical), and brought to focus as a raster format intermediate image. Finally, the image is optically collimated and combined with the viewer's visual field to achieve a spatially stabilized virtual image presentation.

The AIHS Program requires a production display system to be installed and maintained as a helicopter subsystem — designated Aircraft Retained Unit (ARU) — plus each pilot's individually fitted protective helmet, or Pilot Retained Unit (PRU). Microvision's initial concept-demonstration HMD components meet these requirements (Figure 6.2).

Microvision's displays currently employ one horizontal line-rate scanner — the Mechanical Resonant Scanner (MRS) — and a vertical refresh galvanometer. Approaches using a bi-axial microelectro-mechanical system (MEMS) scanner are under development. Also, as miniature green laser diodes become available, Microvision expects to further reduce ARU size, weight, and power consumption by transitioning to a small diode module (Figure 6.1, lower-right) embedded in the head-worn scanning engine, which would also eliminate the cost and inefficiency of the fiber optic link.

For the ACIS project, a four-beam concurrent writing architecture was incorporated to multiply by 4 the effective line rate achievable with the 16-kHz MRS employed in unidirectional horizontal writing mode. The vertical refresh scanner was of the 60-Hz saw-tooth-driven servo type for progressive line scanning. The f/40 writing beams, forming a narrow optical exit pupil (Figure 6.3), are diffraction-multiplied to form a 15-mm circular matrix of exit pupils.

The displayed resolution of a scanned-light-beam display[5] is limited by three parameters: (1) spot size and distribution as determined by cascaded scan-mirror apertures (*D*), (2) total scan-mirror deflection angles in the horizontal or vertical raster domains (*Theta*), and (3) dynamic scan-mirror flatness under normal operating conditions. Microvision typically designs to the full-width/half-maximum Gaussian spot overlap criterion, thus determining the spot count per raster line. Horizontal and vertical displayable spatial resolutions, limited by (*D*)*(*Theta*), must be supported by adequate scan-mirror dynamic flatness for the projection engine to perform at its diffraction limit. Beyond these parameters, image quality is affected by all the components common to any video projection display. Electronics, photonics, optics, and packaging tolerances are the most significant.

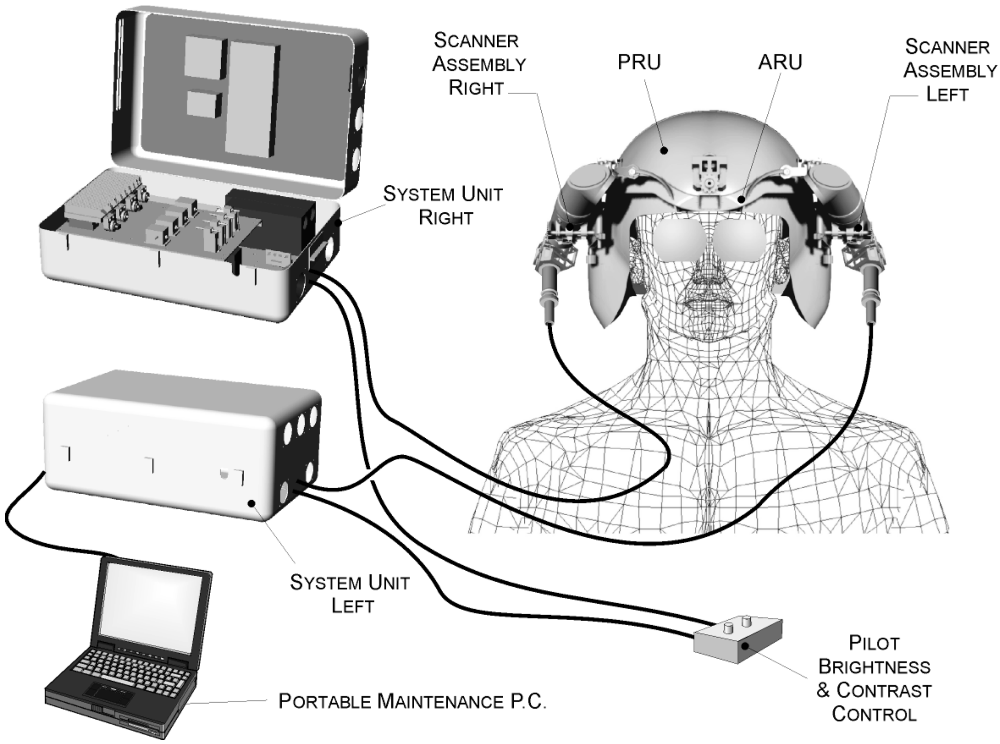

FIGURE 6.2 Microvision's RSD components meet the requirements of the AIHS HIDSS program for an HMD.

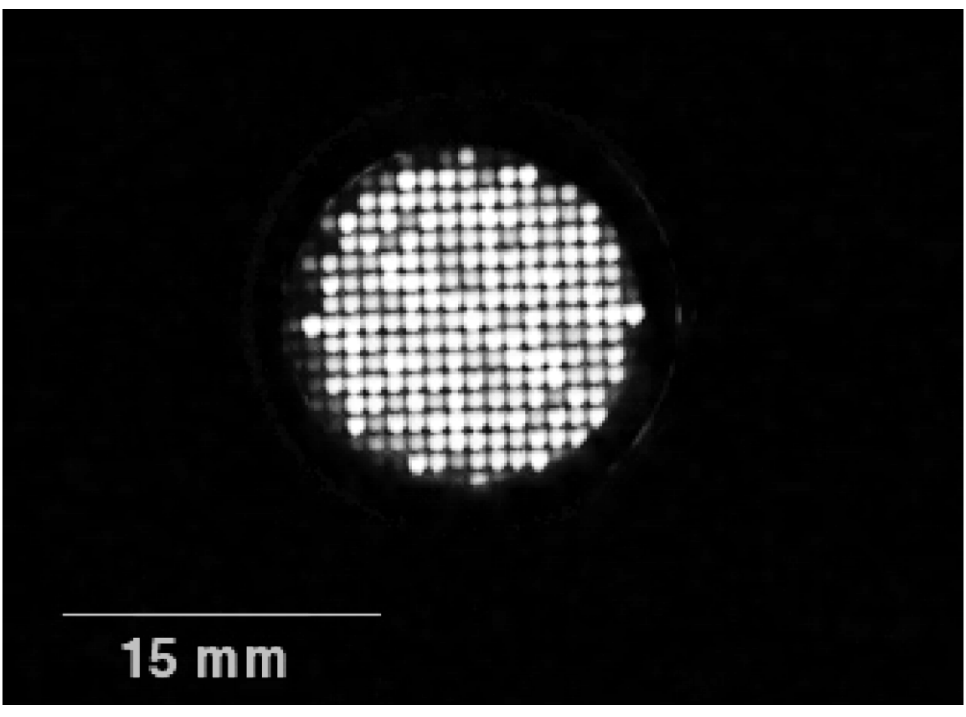

FIGURE 6.3 The far-field beamlet structure of a spot-multiplied (expanded) RSD OEP. The unexpanded 1-mm exit pupil is represented by a single central spot.

6.6.1 Government Testing of the RSD HMD Concept

Under the ACIS program, the concept version of the Microvision RSD HMD was delivered to the U.S. Army Aeromedical Research Laboratory (USAARL) for testing and evaluation in February 1999.[6]

As expected, the performance of the concept-phase system had some deficiencies when compared to the RAH-66 Comanche requirements. However, these deficiencies were few in number and the overall performance was surprisingly good for this initial development phase. Measured performance for exit pupil, eye relief, alignment, aberrations, luminance transmittance, and field-of-view met the requirements completely. The luminance output of the left and right channels — although high, with peak values of 808 and 1111 fL, respectively — did not provide the contrast values required by Comanche in all combinations of ambient luminance and protective visor. Of greatest concern was the modulation transfer function (MTF) — and the analogous Contrast Transfer Function (CTF) — exhibiting excessive rolloff at high spatial frequencies, and indicating a "soft" displayed image.

6.6.2 Improving RSD Image Quality

At the time of this writing, the second AIHS program phase is concentrating on imprving image quality. Microvision identified the sources of the luminance, contrast, and MTF/CTF deficiencies found by USAARL. A few relatively straightforward fixes such as better fiber coupling, stray light baffling, and scan-mirror edge treatment are expected to provide the luminance and low-spatial-frequency contrast improvements required to meet specification, but MTF/CTF performance at high spatial frequencies have presented a more complex set of issues.

Each image-signal-handling component in the system contributes to the overall system MTF. Although the video electronics and AOM-controller frequency responses were inadequate, they were easily remedied through redesign and component selection. Inappropriate mounting of fixed fold mirrors in the projection path led to the accumulation of several wavelengths of wave-front error and resultant image blurring. This problem, too, is readily solved.

The second class of problems pertains to the figure of the scan mirrors. Interferometer analyses of the flying spot under dynamic horizontal scanning conditions indicated excessive mirror surface deformation (~2 peak-to-peak mechanical), resulting in irregular spot growth and reduced MTF/CTF performance (Figure 6.4).

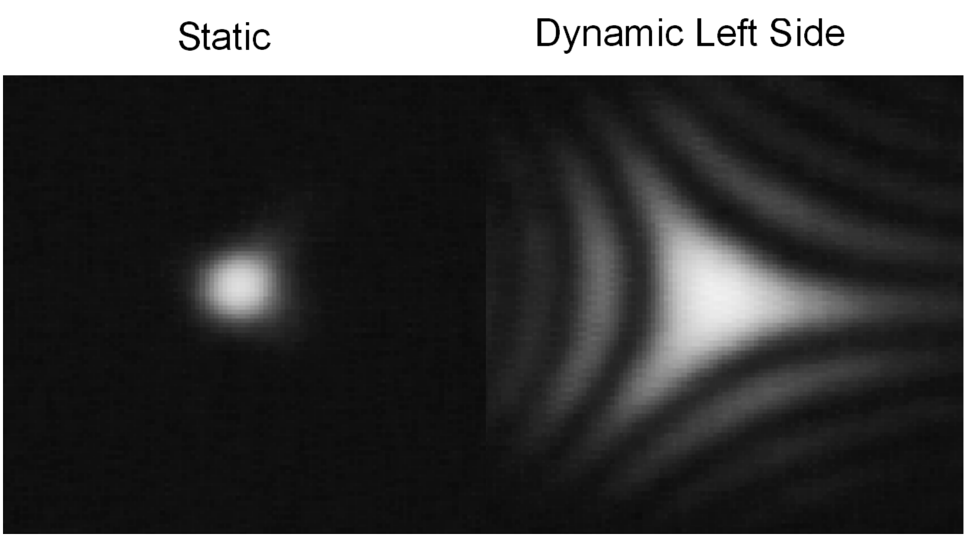

FIGURE 6.4 The effect of improved mirror design is visible in these spot (pixel) images, normalized for size but not for intensity, for scanned spots at ~$\lambda/4$ P-P mechanical mirror deformation (left image), and ~2λ P-P mechanical mirror deformation (right image).

Three fast-prototyping iterations brought the mirror surface under control ($\sim\lambda/4$) to achieve acceptable spot profiles at the raster edge. Thus, the component improvements described above are expected to result in MTF/CTF performance meeting U.S. Army specification.

6.7 Next Step

The next step in the evolution of the helicopter pilot's laser HMD is the introduction of daylight-readable color. Microvision first demonstrated a color VGA format RSD HMD in 1996, followed by SVGA in 1998. Development of a 1280×1024-color-pixel (SXGA) binocular HMD project is being made possible by ACIS's Virtual Cockpit Optimization Program (VCOP), which begins with software-reconfigurable virtual flight simulations in 2000 and proceeds to in-flight virtual cockpit demonstrations in 2001. For these demonstrations, the aircraft's traditional control-panel instrumentation is expected to serve only an emergency backup function. Figure 6.1, with which this chapter began, represents the VCOP RGB application concept.

One configuration of the VCOP simulation/operation HMD acknowledges the limited ability of the blue component to generate effective contrast against white clouds or blue sky. Because the helmet tracker used in any visually-coupled system will "know" when the pilot is "eyes out" or "head down", the HMD may employ graphics and imaging sensor formats in daylight readable greenscale, combined with red, for "eyes out" information display across established green/yellow/red caution advisory color codes, switching to full color formats at lower luminances for "head down" displays of maps, etc.

The fundamental capabilities of the human visual system, along with ever increasing imaging sensor and digital image generation bandwidths, require HMD spatial resolutions greater than SXGA. For this reason, the US Air Force Research Laboratory has contracted Microvision Inc. to build the first known HDTV HMD (1920×1080 pixels in a noninterlaced 60 Hz frame refresh digital video format). The initial system will be a monocular 100-fL monochrome green fighter pilot training HMD with growth-to-daylight readable binocular color operation.

An effort of 30 years has only scratched the surface of the HMD's pilot vehicle interfacing potential. It is expected that the RSD will open new avenues of pilot-in-the-loop research and enable safer, more effective air and ground operations.

Defining Terms

Optomechatronic: Application of integrated optical, mechanical, and electronic elements for imaging and display.

Helmet-Mounted Display (HMD): Head-Up Display (HUD); Head-Down Display (HDD).

ROSE: Raster Optical Scanning Engine.

Virtual Image Projection (VIP): An optical display image comprised of parallel or convergent light bundles.

Image Viewing Zone (IVZ): The range of locations from which an entire virtual image is visible while fixating any of the image's boundaries.

Optical Exit Pupil (OEP): The aerial image formed by all compound magnifiers, which defines the IVZ.

Retinal Scanning Display (RSD): A virtual image projection display which scans a beam of light to form a visible pattern on the retina. The typical 15-mm OEP of a helmet-mounted RSD OEP permits normal helmet shifting in operational helicopter environments without loss of image. Higher-*g* environments may require larger OEPs.

Virtual Retinal Display (VRD): A subcategory of RSD specifically characterized by an optical exit pupil less than 2 mm, for Low Vision Aiding (LVA), vision testing, narrow field of view, or "agile" eye-following OEP display systems. This is the most light-efficient form of RSD.

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Further Information

Microvision Inc. Website: www.mvis.com.