MEMS Display: Emerging Technology for Next Generation Avionics Display

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ABSTRACT
Avionics display systems using CRTs as core of the projection system suffer from reliability issues added to increased weight and cost of the associated circuitry. Though CRTs offer some advantages in the form of good brightness and contrast ratio even in the high ambient light conditions, recent advancement in microelectomechanical system (MEMS) based display technology ushered in an era of miniature displays having low power consumption and better reliability. Digital Micromirror Device (DMD) array from Texas Instruments and Laser Scanning Displays (LSD) have shown enormous potential to be the suitable replacement to the CRTs in air-borne applications. Head up Displays (HUD) using DMD micromirror array and a novel Head Mounted Display (HMD) technology known as the Retinal Scanning Display (RSD) using LSDs are being tested and further improved to meet the military standards.

General Terms
Displays, Flight Navigation

Keywords
Digital Micromirror Device (DMD), Laser Scanning Displays (LSD), Microelectromechanical systems (MEMS) display, Retinal Scanning Display (RSD).

1. INTRODUCTION
Since the first manned flight built by Wright brothers took off in Kitty Hawk, North Carolina, USA on 17th December 1903 and subsequent advancement in aviation industry, there has been a constant effort throughout the world to provide more and more visual information to the pilot inside the flight cockpit to improve his situational awareness for increased flight safety and better maneuvering ability. From the initial mechanical era dials and gauges to current Helmet Mounted Displays (HMDs) and Virtual Retinal Displays (VRDs), the whole concept of information delivery to the pilot has undergone a sea change in past decades with newer techniques being explored and implemented with an aim to achieve better reliability and improved functionality. The Electronics Flight Instruments Systems (EFIS) is the modern cockpit display system which usually consists of a Primary Flight Display (PFD), Multi Function Display (MFD) and engine indicating and crew alerting system (EICAS) display. Similarly, the Head Up Displays (HUD) and Retinal Scan Displays (RSD) also form a part of the avionics display system, mainly in military aircrafts. In recent years, HUD installations have been classified as primary flight instruments [1]. The use of HUD as a vital display unit dates back to mid 1960s when it was first used in the UK Royal Navy Buccaneer for weapon aiming purpose. This paper focuses on HUDs, HMDs and recent developments in their underlying display technologies involving MEMS mirrors. Key elements of a conventional head up display system include: 1. display source, typically a CRT tube which converts the electrical signal to optical signals and displays the symbology; 2.an optical assembly consisting of lenses and mirrors to guide and project the optical signal; 3. a beam combiner: which is a glass plate or a combination of glass plates with semi-reflective coating tuned to reflect only the peak spectral wavelength emitted by the display source, and 4. an electronics set-up which generates various drive signals for symbology generation and internal health monitoring of HUD system.

The CRT is the core of the display system having the advantages of high brightness, good resolution and good contrast ratio levels even in the high ambient light conditions. But the main problem with CRT is the requirement of dedicated and special electronics circuitry such as high voltage power supply, high bandwidth deflection amplifiers which makes the system more expensive and less reliable [2],[3]. The daytime operation of HUD requires a slow cursive writing system which must produce a sufficiently bright display that can be viewed against direct sunlit cloud. For producing such high intensity symbols on the beam combiner with a typical reflectance of 30% (plus other losses), the brightness value at the CRT screen must be typically in excess of 30,000 Cd/m^2 [4]. To generate symbols with such high intensity, the CRT is driven at the high end of its brightness operating range which leads to excessive wear on the tube phosphor, reduces the life of the CRT and MTBF of the whole system [5]. Reliability issues coupled with size, weight and cost consideration regarding the CRT technology has led to the quest for a more efficient technology that can match the brightness and contrast ratio levels offered by the CRT system.

The brightness of a display system depends mainly on the light source whereas the contrast ratio is a function of the characteristics of the image modulator. Unlike the CRT, that acts both as light source and image modulator, the emerging display technology focuses on a suitable light source which is reliable in airborne environment and an efficient image modulator which provides required contrast ratio for avionics applications. Two such potential display technologies are Digital Micromirror Device (DMD), developed by Texas Instruments in 1987 and laser scanning display (LSD) involving MEMS micromirrors. This paper is organized as follows. Section II discusses the DMD technology and its application in avionics while laser scanning displays and its application to HMDs and RSD has been covered in Section III; Section IV provides a comparison between these two technologies with respect to their cost, efficiency, thermal behavior, image quality, circuit complexity, and memory requirement.

2. DIGITAL MICROMIRROR DEVICES (DMD)

The DMD™ is an array of light reflecting mirrors having two stable states and can be actuated electrostatically to either of those states. The DMD™ is both a MEMS device and a Spatial Light Modulator (SLM), as the highly reflective micromirrors are used to modulate the light source and hence it also falls into the category of optical MEMS devices [6].

2.1 Operating principle

The micromirrors of DMD™ have two stable states i.e.: +12 (or +10) degrees (positive state) and -12 (or-10) degrees (negative state) for current DMDs in operation. These two positions determine the direction in which the light is deflected (see Figure 1). The positive state deflects light from the illumination source towards the projection optics and hence known as the ON state whereas the negative state deflects the light away from the projection optics and towards a heat sink and hence known as the OFF state [7].

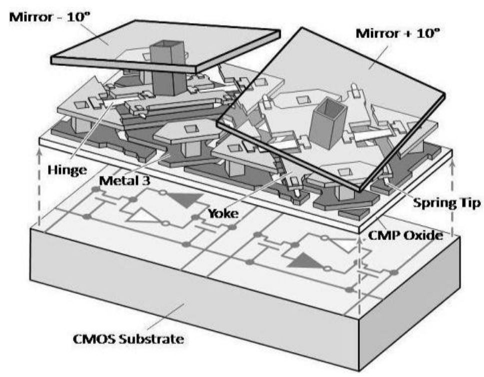

Figure 1: Two DMD mirrors and their components (Picture Courtesy of L.J Hornbeck from [8])

The state of the SRAM cell determines the direction in which the mirrors would be deflected. To display a particular image, the mirrors are modulated accordingly to represent an ON or OFF pixel and to produce different intensity levels (see Figure 2)

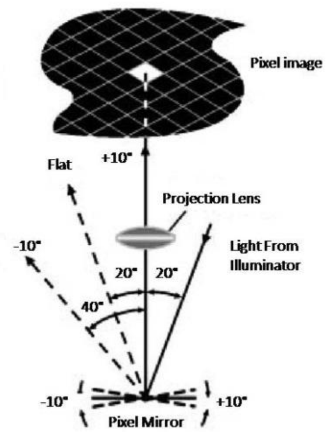

Figure 2: DMD optical switching principle (Picture Courtesy of L.J Hornbeck from [9]. © IEEE)

To produce a darker pixel, the mirrors are kept in the OFF position for a longer period of time than in the ON position during the total frame duration. The large rotation angles and the beam-steering action of the DMD provide better contrast ratio and superior brightness uniformity across the projection surface. The micro-mirrors have fast mechanical switching time of around 15 µs which is around 1000 times faster than a liquid crystal display and optical switching time of 2 µs which enables them to have higher contrast ratio [10].

2.2 Application to avionics display

Any display system for the airborne application requires high reliability and performance parameters which are strictly in accordance with the military standards. Keeping in view the stringent standards, it is really a challenge to find a suitable alternative to the CRTs for avionics application, especially for HUD systems. However, the DMD™ based system coupled with the laser light source has proved its ability to produce required output intensity and is capable of meeting the military environmental standards, when ruggedized [2].

So far as other avionics displays like the multi functional displays and other assistive displays are concerned, DMD™ modules can be configured to have full color operations by following either of the two color management architectures i.e. sequential color management or additive color management architecture. In sequential mode, full color is generated by interposing a color wheel comprising the three primary colors i.e. red, green, blue color filters between the light source and the DMD™ device. Each of the three color field is generated one after the other in each refresh frame. The eye integrates the image fields into one because of the fast switching speed and the whole image appears continuous to the observer. The advantage of this system is that it generates full color by using a single DMD™ device; on the other hand, its efficiency is limited since it uses only one third of the illumination source spectrum at any given time [11]. In additive color management mode, three different micro displays are used with each one illuminated by a light source of its corresponding color. The outputs of the individual micro displays are then integrated using a color combination system to generate full color image.

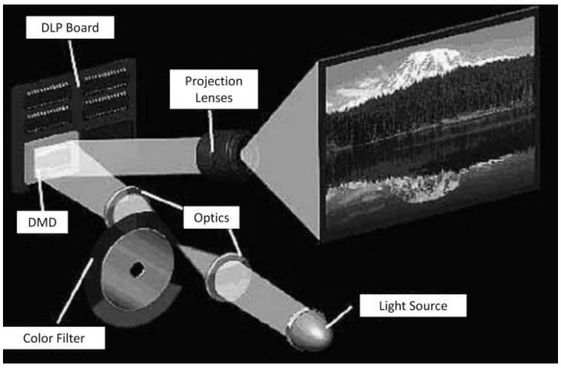

Figure 3: Full color generation using DMD™ in sequential mode (Picture Courtesy of Texas Instruments from [10])

Figure 4 gives the schematic of a DMD-laser light engine based HUD which has been implemented by using a solid state laser device having 1064 nm wavelength at CMC electronics by Billings et al [2],[3]. The light source output has been frequency doubled to produce 532 nm green light for symbology generation. The HUD system is implemented

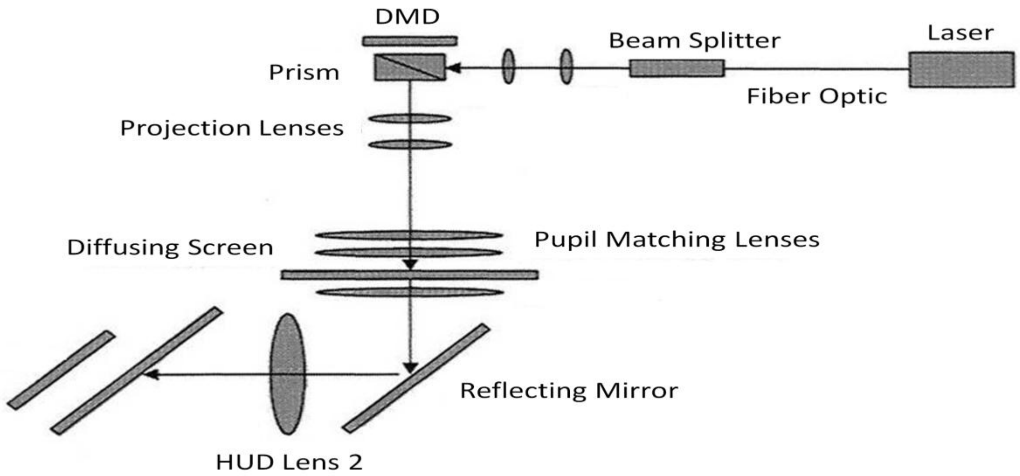

Figure 4: DMD Laser Head-up Display Schematic (Adapted from [2] with permission. © SPIE)

using the DMD module from a commercial DMD projector, which is further modified to meet the HUD requirements. The DMD module uses a subset of the available 1024 X 768 pixel DMD display to produce a 1: 1 aspect ratio display. The overall optical efficiency of the system achieved is about 5% with a maximum luminance of 6800 Cd/m^2 [3].

The DMD based display system provides a fill factor of greater than 90 per cent and its fast switching ability eliminates the image streaking and other motion artifacts. As far as the reliability issues are concerned, Texas Instruments has performed a number of accelerated life testing through vibrational as well as thermal cycling technique. Using Failure Modes and Effect Analysis (FMEA) technique DMDTM life time is estimated to be in excess of 100,000 hours [12]. In the accelerated life testing, the mirrors are cycled at a much faster rate than they would be subjected to during normal operating conditions. The micromirrors are also found to perform satisfactorily under vibration and shock testing as the resonant frequency response of the mirror is in the range of 100 KHz to 2MHz which is much higher than the normal operating frequencies [13].

3. LASER SCANNING DISPLAY (LSD)

Unlike the DMD which contains millions of micromirrors requiring a high yield fabrication process, the Laser Scanning Display (LSD) uses a single MEMS device to scan a laser beam on the projection surface or on the retina of the viewer directly in case of Retinal Scan Displays (RSD) to display the required image.

3.1 Operating principle

LSD mainly employs a laser deflection mechanism which can be implemented using either a bi-axial mirror or a set of two uni-axial mirrors. The purpose is to move the beam both in horizontal direction with a fast scan rate and in vertical direction with a slow scan rate to produce the required frame rate in a raster scan image. The bi-axial mirror tilts in orthogonal directions whereas in case of uni-axial mirrors, one mirror moves in the horizontal direction and the other in vertical direction to effectively produce deflections in both the directions.

The micromirrors are usually actuated through electrostatic or electromagnetic means which enable sufficient deflection of the mirrors to achieve the required resolution. A gimbal-less bi-axial micromirror using an electrostatic comb-drive actuator proposed by Milanovic et al of the Adriatic Research Institute, Berkeley [14] achieves high-speed laser beam-steering in both axes having optical scan angle of up to 16° on each axis with a diameter of 0.8 mm. The stereo microphotograph of the scanner is shown in fig 5. The micromirror scanner can be driven from DC to about 4 kHz without resonance. Using a fisheye lens in front of the micromirror, a projection angle of over 100° can be achieved.

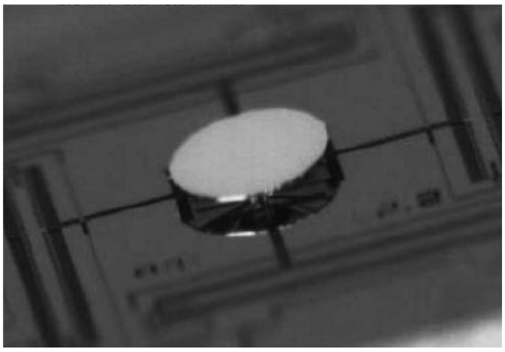

Figure 5: Gimbal-less two-axis micromirror scanner (Picture Courtesy of V Milanovic from [14]. ©IEEE)

LSDs using electromagnetic actuator consume significant current as well as have increased weight and size of the scanner engine. But they are capable of providing greater torque than the electrostatic actuators at small voltage. Application requirements determine the type of actuator needed for a particular scanner.

Another novel biaxial electromagnetic actuator proposed by Yalcinkaya et al uses a magnetic field laterally oriented 45° to the orthogonal axes producing large scan angles at low actuation power. In this approach, current carrying conductors are embedded in the outer frame of the mirror which interacts with the external magnetic field produced by a permanent magnet. This gives rise to a Lorentz force which produces the required torque in the two scan directions (see Figure 6). The frequency of the applied torque is adjusted to excite the resonant mode in the horizontal direction at 21.3 kHz and to provide 60 Hz vertical driving signal [15].

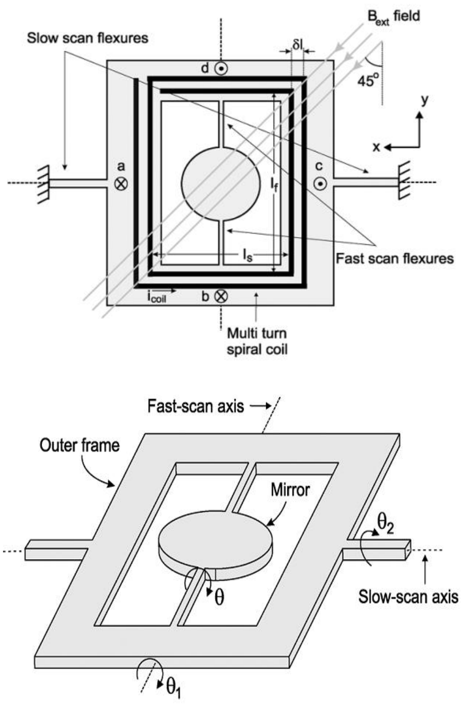

Figure 6: Schematic of the biaxial microscanner proposed by Yalcinkaya et al (Picture Courtesy of A.D. Yalcinkaya from [15]. © IEEE)

3.2 Application to avionics display

A novel head mounted display technique, known as the Retinal Scanning Display (RSD), uses the LSD concept to scan a laser beam directly onto the human retina. There are several ways to implement such a scanner. One of such earlier systems developed at Delft University [16] used a high speed rotating polygon mirror to produce retinal scanning. Tom Furness at the HIT Lab of the University of Washington used a resonant mirror scanner to produce high speed scanning of the light beam to implement a virtual retinal display [17]. Other methods include acousto-optic scanner, electro-optic scanner and holographic scanners. Microvision Inc. has developed a full retinal display by using biaxial MEMS scanner discussed earlier which also uses a resonant scanner for fast horizontal scan [15],[18],[19]. The system developed by Microvision Inc. is shown in Fig 7 [15].

The main components of a RSD system are drive electronics, a photonics module, scanner and exit pupil expander or viewing optics. Based on the received video input or graphic input from the image source, the drive electronics controls the intensity levels, pixel positioning, color components that are required to display the image. The photonics module is connected to the helmet unit through optical fiber and through it light beam of desired intensity and color components travels to the scanner module. Pixel intensity can be controlled either by direct modulation in case of semiconductor laser and LED based systems or indirectly by using an external modulator such as acousto-optic and electro-optic modulators in case of solid state laser and gas lasers. The scanner module directs the beam received from the photonics module to the image space in a raster format.

Typical exit pupil size of RSD systems is around 1-2 mm. Hence to provide some tolerances in head positioning and eye pupil movement, exit pupil expander (EPE) is used which increases the exit pupil size to around 10-15 mm. EPEs are implemented using diffractive optical elements or micro-lens array for monochrome and color display applications respectively [20],[21]. A small exit pupil requires an eye pupil tracking system to avoid loss of information during eye movement whereas a large exit pupil may result in vignetting and a limited depth of field. Hence the exit pupil size needs to be optimized depending upon the display application [22].The scanning laser RSD concept led to the further miniaturization of HMDs with reduced cost and weight while eliminating the need of CRTs. It also offers high brightness potential, full color capability and diffraction limited resolution. But the excessive roll-off of the frequency response of Modulation Transfer Function (MTF) and Contrast Transfer Function (CTF) of such systems at higher spatial frequencies needs to be improved as well as the requirement to increase the spatial resolution beyond SXGA (1280 X 1024) to accommodate high bandwidth image sensor and digital image data needs to be addressed [23].

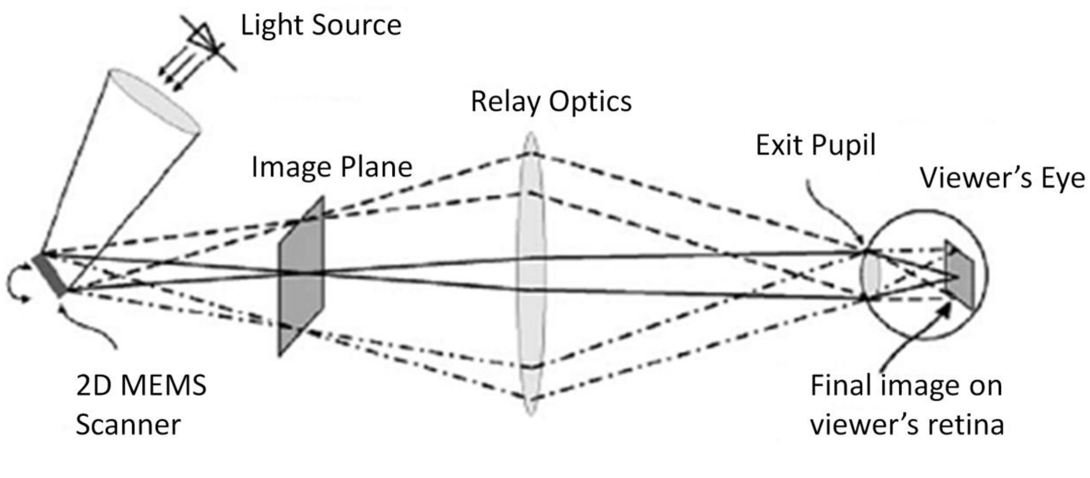

Figure 7: Schematic of the RSD system (Picture Courtesy of A.D. Yalcinkaya from [15]. © IEEE)

4. MICROMIRROR ARRAY VS LSD – A COMPARISON

Though both scanning mirror display and displays involving a micromirror array (e.g. DMD array) have the potential to improve the reliability and cater to the growing needs of the avionics display systems, both the systems differ from each other with each having some unique characteristics which can be used to meet different application requirements.

4.1 Manufacturing Cost

In case of micromirror array, there is a one to one mapping between the displayed pixels and the number of micromirrors in the array whereas in case of laser scanning display a single micromirror sequentially scans across the projection surface to display the input image. Hence a high-yield requirement in the fabrication process ensuring required accuracy has to be met in case of micromirror array. This increases the process complexity of fabrication which also increases the manufacturing cost of micromirrors. But in case of LSD, we require only a single micromirror to scan the laser beam allowing simpler fabrication process and mass production at reduced cost.

4.2 Efficiency

Power efficiency of display systems is usually expressed in terms of Lumens per watt i.e. total optical power output (Lumens) at the display surface per total electrical power input (watt) to the device. In case of avionics display, the overall efficiency will depend on the product of the efficiencies of all the optical components starting from the light source to the beam combiner or the exit pupil optics, as the case may be. In case of micromirror array, the illumination source is constantly ON irrespective of whether a pixel is actually ON or OFF whereas in case of LSD, we directly or indirectly modulate the laser source according to the pixel information. Hence to represent a darker pixel the source intensity is reduced accordingly thereby minimizing power requirement. Therefore the scanning laser system provides better efficiency than the micromirror array systems which also gets enhanced by the superior efficiency of the laser source used in LSDs over the efficiency of the fluorescent lamps or LEDs used in micromirror array.

4.3 Thermal Issues

As discussed earlier, a micromirror display requires a continuous illumination which causes more off-state light to be trapped within the device. This can cause undesired thermal effects requiring an efficient cooling system or designing a suitable heat sink.

4.4 Image Quality

One of the advantages of the micromirror display system is by using as many numbers of mirrors as the number of pixels of the displayed image, the mirrors are allowed to operate in only two stable states i.e. either + 10° or -10°. But in case of LSDs, the micromirror should operate at high scanning frequency and with a wide projection angle to achieve required resolution and frame rate. High acceleration forces required for high scanning frequency often cause bending of the micromirror. Even a small deformation of the mirror flatness can lead to pixel and image distortion [24]. The resolution of LSD system is a function of the product of scan angle and mirror size (Θ*D). Taking into account the required resolution, frame rate, mechanical and space constraints, the mirror size and scan angles are optimized to meet the application needs [25].

4.5 Circuit Complexity and Memory requirements

As the micromirror array displays the whole image frame in its entirety, it requires more memory and more complex circuitry than the LSD system. But when it comes to display resolution, micromirror array like the DMD system has been able to produce true 1080p HD display with full 1920 X 1080 pixels on the screen, a feat which is yet to be matched by the LSD system with same picture quality as the DMD.

4.6 Speckle

Speckle is a random interference pattern that is inherent to systems using coherent light sources. So in case of LSDs, random scattering of laser from the projection surface gives rise to speckle pattern that reduces the overall contrast ratio and image quality. However, several techniques such as diffractive optical element based exit pupil expander [21] and dynamic polymer based diffraction grating [26] have been proposed to minimize this undesirable visual artifact. Micomirror arrays using non coherent light sources do not suffer from speckle interference and hence they offer a better image quality in this regard.

5. CONCLUSION

MEMS displays offer many advantages like miniaturization, reliability, cost and weight reduction in addition to the fact that they can be ruggedized to meet military standards for air-borne applications viz. avionics displays. Other MEMS based display technology like Grating Light Valve (GLV) and reflective and transmissive Liquid Crystal on Silicon (LCOS) displays are also being explored for their suitability to avionics display [2], [27]-[29]. LSD based RSDs revolutionalized the head-worn display technology with better resolution and full color capability. Similarly, DMD based display systems have undergone extensive testing under varying temperature, shock and vibration levels and its performance under these conditions makes it a good candidate for avionics display. But the search for a suitable light source in case of DMD and the need to achieve higher scan rate, better contrast ratio, and safety issues associated with laser source will be the major research areas in the field of avionics display.

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