Chapter 8

DISPLAY AND IMAGING SYSTEMS

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8.1 Introduction

MOEMS technology combining MEMS and micro-optics is well suited for manipulating light. A number of different ways can be envisioned to scan, steer, or modulate light beams using tiny electromechanical structures. MEMS mirrors or microlens arrays can be used to change the light beam propagation direction for scanning or modulating the beam, and diffraction gratings, optical choppers, or microinterferometers can be used as light modulators. MOEMS technology allows a large array of micromechanical light manipulators to be batch-fabricated at low cost. A good example of a successful MOEMS display product is the Texas Instruments digital micromirror device (DMD) display, which probably has the largest number of moving mechanical components (over 1 million) of any product. On the other hand, there are several cases where MEMS technology has not provided any performance and/or cost advantages over other methods of machining and assembly of components and devices.

A number of MOEMS display and imaging products and technology demonstrators have been developed for defense, aerospace, industrial, medical, and consumer markets in the form of wearable displays, projection displays, imaging devices, barcode readers, and infrared imaging cameras. There are several alternative system architectures for these devices. In scanning beam systems, one biaxial or two uniaxial scanners can be used to draw a 2D raster pattern at some distance from the scanners, and they can be used to display or capture information. Alternatively, an array of micromechanical devices can be used to produce a line or a 2D array of pixels. Each pixel is a microelectromechanical element that displays or senses different pixel intensities or gray levels.

This chapter discusses the application of MEMS technology for displays and visible and IR imaging systems. In the display section, examples of scanning beam and pixel-based display technologies are discussed. The imaging systems section discusses scanning-beam imaging systems and their applications (confocal microscopy, ladar, etc.), aberration correction systems to enhance the capability of scanning systems, and array-based IR imaging systems (such as thermal cameras).

8.2 Display systems

Everybody is familiar with the two dominant display technologies: the cathode ray tube (CRT) and the liquid crystal display (LCD). The CRT was invented more than 100 years ago, and CRT TVs have been on the market since the 1930s. LCD products have been on the market since the late 1960s. Both CRTs and LCDs have found applications in nearly all of the market segments where displays are used. Application of MEMS technology to displays is a relatively new concept. The earliest micromechanical projection display device was the *mirror matrix tube* developed at Westinghouse Research Labs in the mid-1970s.[1] IBM also developed micromechanical light modulators for display applications.[2] Westinghouse and IBM designs both used electron-beam addressing, did not appear to offer significant advantages over CRTs, and did not have any commercial success. K. E. Petersen at IBM demonstrated a projection display using a 16×1 array of single-crystal cantilever micromechanical light modulators and a galvanometric scanner;[3] Petersen also demonstrated silicon torsional mirrors.[4]

Texas Instruments developed the first commercially available high-volume MEMS display device, referred to as the DMD. Micromechanical light modulator research at Texas Instruments began in 1977,[5] and the first DMD-based projection display product was launched in 1996.[6] Now there are a wide variety of commercially available DMD-based display products. Microvision's wearable personal display product, the normal augmented vision system (NOMAD), was introduced in early 2002. A second-generation display product with smaller form-factor and improved performance will be launched in early 2004.[7] There has been significant research activity and technology development of MEMS displays during the past decade, and more products are expected to follow.

MEMS displays can be classified into three groups based on the number of micromechanical elements (or the number of pixel-generating elements): 2D scanner-based displays, 1D scanner- and 1D pixel-array-based displays, and 2D pixel-array-based displays. If N represents the number of pixels in one row or column of the display system, the categories listed above have on the order of N^0, N^1, and N^2 micromechanical elements, respectively.

In this section, three of the most advanced MOEMS display technologies are discussed in detail: (1) retinal scanning display (RSD) technology, which is a 2D scanner-based display technology, (2) grating light valve (GLV) technology, which is an example of a 1D scanner and 1D pixel-array technology, and (3) DMD technology, which is a 2D pixel-array technology. Each of the three has a different system architecture and employs a different optical principle for light modulation. Table 8.1 provides a summary of the features of these technologies. More detailed analysis of the pros and cons outlined in the table are given in Secs. 8.2.1, 8.2.2, and 8.2.3.

In Sec. 8.2.4, we briefly review three additional MEMS display technologies: the thin-film micromirror array (TMA), the interferometric modulator (IMod), and the integrated MEMS optical display system (IMODS) technology.

8.2.1 Retinal scanning displays

The first example of a scanning beam display is the CRT, where an electron beam is scanned onto a phosphor screen. Laser scanning displays scan visible photon beams instead of the electron beam, eliminating the need for the phosphor screen and the vacuum tube, and allowing for easy color multiplexing. One biaxial or two uniaxial scan mirrors can create a 2D raster-scanned image.

RSDs are wearable scanning display systems that create a virtual image at the viewer's retina. RSD technology was invented at the University of Washington Human Interface Technology (HIT) Lab in the early 1990s. It was originally called the Virtual Retinal Display™ (VRD™) and used acousto-optic scanners.[8] Microvision has been developing RSD technology demonstrators and products based on patented miniature scanner technologies, including MEMS scanners.

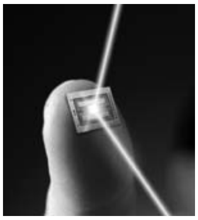
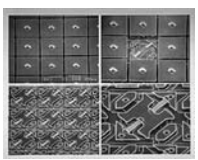
Section 8.2.1.1 details the MEMS scanner requirements, design, and performance for displays, and Sec. 8.2.1.2 discusses the RSD system operation, light source technologies, and applications.

8.2.1.1 MEMS scanners for display applications

There are several laser scanning display implementations using non-MEMS scanners, such as acousto-optic scanners,[8] polygonal scanners,[9] and galvanometric and resonant scanners.[10,11] MEMS scanners were mostly developed during the past two decades. MEMS technology can be used to fabricate the scanner, actuator, and scanner position sensors all integrated on the same chip in one package, which then becomes the heart of the scanning display system. Most of the MEMS scanners are low-inertia galvanometric or resonant scanners.

As discussed in Chapter 7, there are a number of different MEMS scanner implementations, but not all are suitable for display applications. The performance of display systems is judged by the human eye, which is an exceptionally good instrument to sense temporal and spatial artifacts in a displayed image. Thus, the scanner performance requirements for high-resolution displays are difficult to meet. There are several references that discuss MEMS scanners for display applications.[12–15] In this section, we discuss the design and the performance of MEMS scanner technology that meets the requirements for an SVGA (800×600) RSD system.

Table 8.1: Comparison of RSD, GLV, and DMD display technologies.

Technology and number of micromechanical elements	Resolution/ Applications	Light Sources/ Brightness	Optics
($N^0 \sim 1$) RSD  1 Bi-axial or 2 uni-axial Scan Mirrors	Wearable displays: NOMAD, Jan'02 SVGA (800×600)– LED-based color, SVGA cell phone demonstrated Military HMDs	800 fL red-black, SVGA product, using red LD $>$ 30fL full-color, SVGA using R,G,B LEDs	A simple focusing lens and a good quality ocular needed for wearable displays. Very simple optics for projection mode of operation.
($N^1 \sim 10^3$) GLV  1D array of diffraction gratings and horizontal-Axis Scan Mirror	Projector Prototype HDTV (1920×1080) No product	High-power laser light sources: Green and Blue lasers, and Red laser diode bars	Anamorphic beam shaping optics for illumination, a good quality relay lens before scanner and a good quality projection lens after scanner are needed.
($N^2 \sim 10^6$) DMD  2D Micromirror array	Portable Projector/ Digital Cinema SVGA - 1996 (800×600) XGA 1998 (1024×768) SXGA - 2000 (1280×1024)	Arc lamp and color splitting prisms 500 ANSI Lumens 1-chip small projectors 6500 Lumens using 3 projectors	A good quality projection lens is needed.

Color	Fabrication and Yield	Challenges
R, G, B laser light sources or LEDs (diode sources are directly modulatable, lasers require external modulators). Color combining can be done using prisms, waveguides, or electronically with time-delays.	Bulk micromachining. Simple processing steps; yields can be high once process is optimized. Most of the testing can be done before packaging.	G and B lasers are expensive. LED sources have limited brightness. High-Q, low-voltage operation requires vacuum sealing of scanner.
Requires R, G, B lasers, 3-chip GLVs, and color combining prisms are used for color. Multi-wavelength operation of same grating requires system modifications.	Surface micromachining. CMOS compatible process. 1D array yields are substantially better than 2D array yields. Most of the testing cannot be done until after packaging.	G and B lasers are expensive. Coherent artifacts degrade image quality. Due-to scanning, pixel-to-pixel uniformity needs to be exceptionally good.
1, 2, or 3 DMD-chip-based color projectors have been built. One-chip uses color sequential operation. Employs a spinning color wheel. Three-chip operation uses color-splitting prisms.	Surface micro machining. CMOS compatible process. Complicated processing. Most of the testing is done after packaging.	Complicated processing reduces yields for high resolutions. Lamp lifetimes have been a limitation; extended lamp lifetimes now allow application to TVs.

Scan architectures

The display system architecture needs to be decided before the scanner requirements such as mirror size, scan angle, and frequency can be determined. For instance, one has to decide on whether to use two uniaxial scanners or one biaxial scanner, unidirectional or bidirectional scanning, a sinusoidal or other scanner-drive waveform, and single-beam or multibeam scanning.

Figure 8.1 illustrates uniaxial and biaxial gimbal-mounted torsional scanners. Uniaxial scanners have a single axis of rotation, and biaxial scanners have two perpendicular axes of rotation. Note that if two uniaxial scanners are placed one after the other in the optical train (without any relay lenses in between), the rotation of the first scanner causes the optical beam to walk across the second scanner. Thus, the second scanner in the optical train needs to be larger. For a biaxial scanner, the oscillation of the inner frame (the horizontal scan frame, or fast-scan frame) alone creates a horizontal scan line, and the oscillation of the outer frame (the vertical scan frame, or slow-scan frame) alone creates a vertical scan line. If the frequency and the phase of the two frame oscillations can be tightly controlled, one can draw repeated 2D raster patterns that can be used to display images and video. Based on the scanner performance and display size and packaging constraints, the gimbal-mounted biaxial torsional scanner illustrated in Fig. 8.1(b) is a preferred configuration for display applications.

Figure 8.2 illustrates unidirectional and bidirectional scanning. Bidirectional scanning refers to writing or displaying a new line of data in both scan directions, whereas unidirectional scanning refers to writing data only during the forward sweep of the horizontal scanner. Bidirectional scanning doubles the display line rate by permitting the scanner to write two lines during one scan cycle. The drawbacks of the bidirectional scheme are: (1) it requires buffering one line of data and displaying it in reverse order during the backward sweep of the horizontal scanner; (2) it requires precise control of the phase between forward and backward scan lines; (3) it produces nonuniform line-to-line spacing across the horizontal scan line.

One important advantage of laser scanning systems is that one scanner can be used to scan multiple beams simultaneously, thereby improving the horizontal

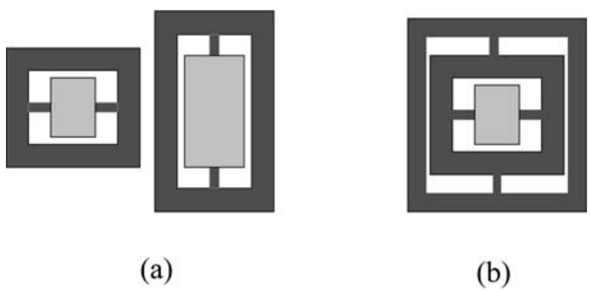


Figure 8.1: (a) Two uniaxial scanners, and (b) a biaxial scanner.

or the vertical resolution of the display. As an example, two-beam bidirectional and four-beam unidirectional scanning can successfully be implemented. In the four-beam approach, each feed beam is coupled to a different light-source modulator, and all beams are combined in a four-channel waveguide. Multibeam scanning multiplies the line rate of the system by the number of beams, thereby reducing the horizontal scanner frequency requirement. The number of parallel scan beams in a given display will depend on a variety of factors, such as the complexity of the overall system, the cost, and optical alignment considerations.

Scan waveforms

The line rate of a 60-Hz-refresh-rate SVGA (800×600 pixels), display is 36,000 lines/s. Using a bidirectional scanning architecture, a horizontal scanner operating at about 19 to 20 kHz is required (18,000 cycles for display plus some time for scanner retraces). At such high frequencies, the only way to lower the power requirement is to take advantage of the mechanical gain, or *Q-factor*, of the scanner by operating the scanner at its mechanical resonant frequency. The resonant sinusoidal motion of the scanner takes up the least amount of power but results in pixel size and brightness variations across the scan line due to scanner speed variations. Typically, writing is halted during the extremities of the scan line to minimize the speed variation. The pixel size and brightness variations during the visible portion of the scan can be easily corrected electronically.

The vertical scanner motion typically has a linear ramp waveform at the refresh rate of the display, which is 60 to 96 Hz in most display systems. An entire video frame is written from top to bottom of the 2D raster, and then the scanner rapidly *retraces* to the top of the raster and starts writing the next video frame. The retrace time in scanning systems is analogous to the retrace time of CRTs and to the blanking time needed to refresh the light valve for liquid crystal displays. Faster retrace

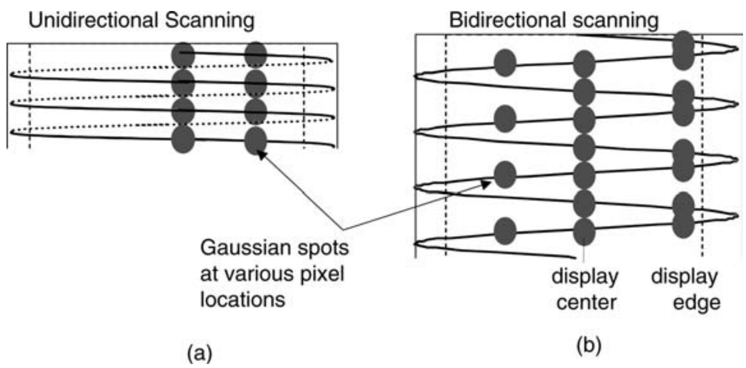


Figure 8.2: Four full raster cycles for (a) one-beam unidirectional scanning, (b) one-beam bidirectional scanning.