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Scanner design and resolution tradeoffs for miniature scanning displays

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ABSTRACT

Miniature displays based on scanning a low power beam directly onto the viewer's retina can offer high spatial and color resolution and very high luminance. For scanning display systems, the resolution is primarily determined by the product of scan-angle and mirror-size (θD-product). Once θD is determined based on resolution requirements, it then remains to choose D and θ. The choice of D and θ has a big impact in scanner design and many factors need to be taken into account. This paper discusses how D and θ should be chosen considering the limitations due to dynamic mirror deformation, stress in flexures, scanner frequency, optomechanical design, size, and cost.

Keywords: Scanner design, scanner resolution, Virtual Retinal Display, VRD, microdisplays, head mounted displays

1. INTRODUCTION

Virtual Retinal Display™ (VRD™) technology is a novel scanning-based display technology where the displayed image is scanned directly onto the viewer's retina (in a raster scan pattern similar to that in a conventional television set) using low-power red, green, and blue light sources, such as lasers or LEDs.[1,2,3] The brightness of the laser-based VRD system is not limited the same way the other display technologies are. The VRD system typically uses spectrally pure lasers as the light source. Therefore, it has better color gamut compared to LCDs and CRTs.

Spatial resolution and image quality of the VRD system is determined primarily by the scanner performance, and also by light sources, modulators, and system design. The most important parameters in scanner design are scanning mirror size (D) and scan angle (θ). In the remainder of this section we briefly discuss the VRD system operation and advantages compared to flat panel display technologies. In subsequent sections, we discuss how D and θ should be chosen to meet resolution, optics design, and mechanical design requirements. Section 6 summarizes the results with a figure showing all θD tradeoffs discussed in this paper.

VRD Operation: Figure 1(b) illustrates the four subsystems (drive electronics, light sources, scanners, and viewing optics) in a color VRD system.[4]

Drive Electronics. Drive electronics receive and process signals from an image or a graphics source. The processed signals contain information that controls the intensity, mix of color, and the coordinates to position the pixels that comprise the image.

Light Sources. VRD uses very low power light sources to create an image a single pixel at a time. With color images, three light sources—red, green, and blue—are modulated and then merged to produce a pixel of the appropriate color and intensity. VRD poses no danger to the eye since it operates at extremely low intensity levels. A study has been conducted[5] which indicates VRD power levels are completely safe in normal operating mode and in failure modes. In addition, the system is equipped with a number of hardware and software safety features that attenuate or block the light automatically in the event of system malfunction.

Scanners. Mechanical horizontal and vertical scanners project one pixel at a time through the viewing optics of the eye to the retina. This process, in effect, "paints" an image by rapidly moving the light source across and down the retina, in a raster pattern, with exacting precision. The current VRD design uses a resonant scanner to sweep the horizontal axis (fast scan) and a non-resonant scanner to sweep the vertical axis (slow scan). The sinusoidal motion of the fast scan combined with the linear motion of the slow scan creates a 2-dimensional sinusoidal raster pattern. Nonlinearities in scanner speed along the scan line can be corrected optically and/or electronically.

Viewing Optics. Refractive, reflective, and diffractive optical elements are used to expand and transmit the scanning beam of light through the pupil and onto the retina to create an image within the viewer's eye. Viewing optics magnification, total optical scan angle and scanning mirror size determine the field of view and exit pupil size. A large exit pupil is desired in certain applications and can be achieved by using a diffractive optical element in the system.

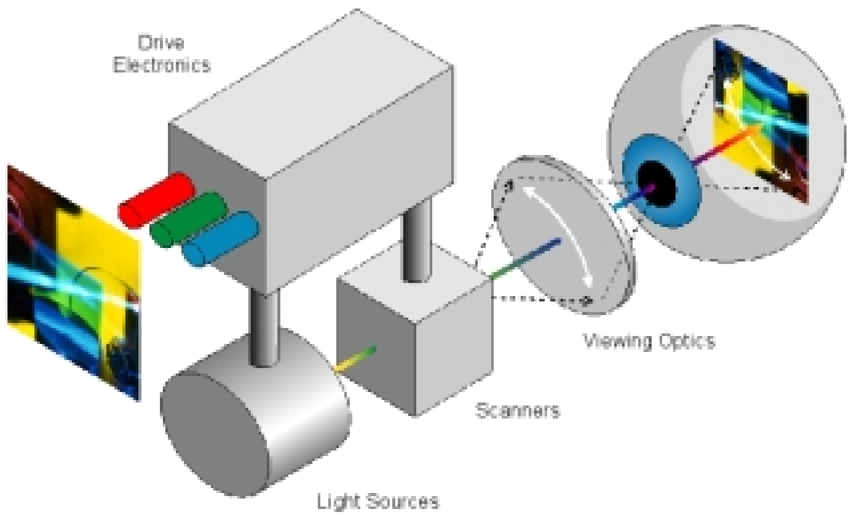


Figure 1: VRD functional diagram.

Technology Comparison: Figure 2 shows a diagram of available technologies for display and printing, emphasizing a fundamental distinction – the number of elements. Matrix displays have in the order of 10^6 pixels that must be defect free, and output matched. With some compromises, this can be achieved, making this technology a winner for notebook computer displays. However, increased pixel count, increased speed requirements and optically constrained minimum pixel sizes coupled through superlinear yielded-wafer-area-costs limit this approach. Compounded with these problems of multiplicity is the additional highly constrained problem of providing a controlled amount of light at each pixel. The numerous competing approaches shown in Figure 2 is a testimony that no one of them has yet met all the requirements.

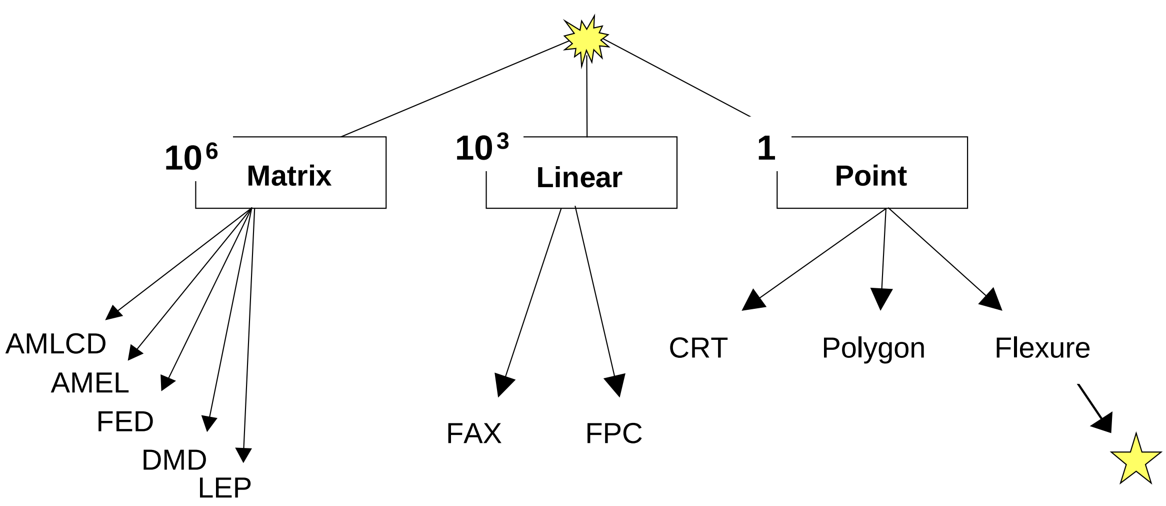


Figure 2: Technology selection logic for microdisplays.

Technologies based on scanning in one dimension use linear array of about 10^3 pixels and can provide high resolution and good image quality. Correlation of pixel variations in the scan direction leads to more stringent matching conditions than either the matrix or point approach. That these problems can be overcome, at the cost of speed and complexity, is demonstrated by applications such as fax and document scanners, and cameras that scan a linear array through a lens focal plane. The speed and size of the transport mechanism make this approach unattractive for microdisplays. In addition, for display applications, the well-matched linear arrays of emitters are not as well developed as linear CCD arrays.

Displays and image capture devices using scanners sweep a point (containing 1 or a few pixels) across the screen and can create megapixels using one or two scanners. The CRT, based on scanning, has been the dominant display technology for years. However, their large size, and lack of color mask at small sizes make it unsuitable for microdisplays. By switching from an electron beam to a photon beam, the bulk of the vacuum bottle is eliminated, wavelength multiplexing is enabled, and the advantages of scanning retained. This is the winning approach to desktop and office printing, as exemplified by laser printers. Although the images are high resolution, the speeds are seconds per image, far short of what is required for dynamic display applications. This limitation is traced to the polygon scanners, which do not meet the simultaneous size, speed and resolution requirements for a microdisplay.

Flexure based scanners have the potential to enable a point based display to meet the simultaneous requirements of speed, resolution, size, and cost. If that can be done, then all the other advantages that are demonstrated by other scanning systems ensue. For example, the single scanned pixel can be very well controlled in comparison to the compromises needed to treat 10^6 pixels of a matrix. A wide variety of pixel implementations are available, both sources and detectors, including bulk devices since only one or a few are required. For example, the pixel could be a direct view of a laser diode, or could be the view of a fiber core. In the fiber case, the light source, modulation, and data source can all be remotely located, thus enabling the lightest weight head mounted displays.

VRD technology can provide very high luminance, high color resolution and spatial resolution, and high contrast. MEMS scanner technology is well suited for mass production at low cost. MEMS scanners have significant advantages compared to matrix displays in terms of wafer area and yield especially for SVGA and higher resolutions. The VRD is well suited for numerous applications across several market areas (e.g., military, medical, simulation, portable communications, entertainment) and in a wide array of products ranging from helmet/head-mounted displays for military command-and-control, medical, and information display environments.

2. SCANNER DESIGN

Miniature displays demand high-resolution (megapixels or higher), high-frequency, small-size, small-weight, low-power, and better than 0.1% position accuracy from scanners. Two uni-axial scanners or one bi-axial scanner is needed to create a 2-D raster pattern. There are many ways to support mirrors, including hinge, bearing, and flexural designs.[6] The scanning mirror must be supported and constrained to move only about the scanning axis. Any off-axis motion can cause image shift, distortion, and loss of resolution and contrast. Given the video scanning requirements, torsional flexures are the preferred configuration for VRDs, providing repeatable, controllable motion with a minimum of piece parts. Figure 3 shows the geometry for a torsional scanner. They can be easily fabricated and have fewer wearout and dead space issues.

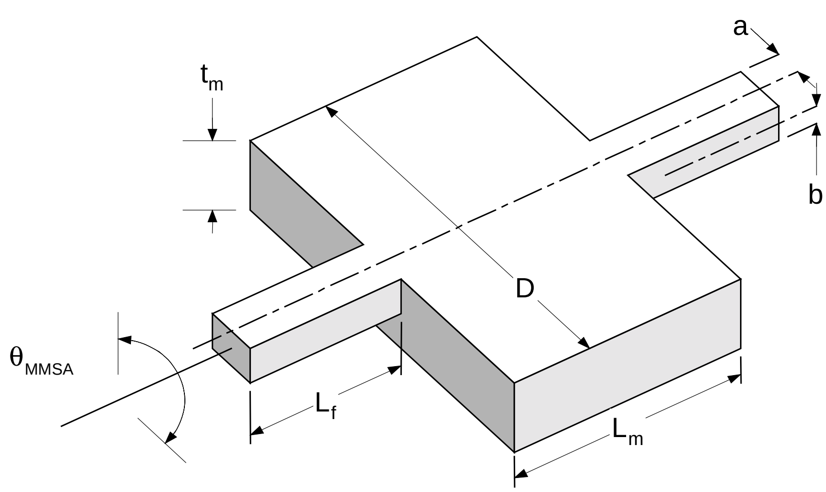


Figure 3: Torsional resonant scanner geometry

Symbol	Meaning
θ or θ_{MMSA}	Maximum mechanical scan angle (MMSA), 0-to-peak
D	Mirror Width
L_m	Mirror length (L_m = D for square mirrors)
t_m	Mirror thickness
L_f	Single flexure length
a	Flexure half-width (long side)
b	Flexure half-thickness (short side)

As discussed in the next section, θD can be found using the resolution requirements of the display system. Once θD is determined, it then remains to chose appropriate values of D and θ. At first, it may seem like large mirrors are best. For instance, large mirrors ease alignment to the beam and optical interface, and minimize optical projection errors. However, as described in more in detail in subsequent sections, several factors mitigate against large mirrors. For example, for square mirrors, inertia grows as D^4, thus, large mirrors carry a heavy penalty in frequency. Note that thicker flexures (stiffer flexures) can be used to bring the frequency back up, however, high torsional stress in the flexures and packaging considerations limit the range of values for the flexure width and length. The dynamic flatness of the mirror is an even stronger function of mirror width, increasing as a function of D^5. Mirror flatness directly affects the optical quality of the system. In addition, large mirrors take up more space, which leads to larger system size. If the parts are batch fabricated, the mirror size also translates directly into cost, as fewer parts can be made on a given wafer. For these reasons, it can be very difficult to build large, fast structures.

Small mirrors are not the answer either. While, in general, small mirrors can achieve higher frequencies, the large scan angles needed to meet the resolution requirements may result in flexure stresses that exceed the yield strength of the material. Note that making the flexures longer and thinner reduces the flexure stress. However, long and thin flexures result in energy coupling to modes other than the torsional mode of the oscillator, thereby degrading the image quality and reducing drive efficiency. Depending on the material, large scan angles can also affect the lifetime and stability of the scanner.

In general, video applications are a severe test of mechanical scanners, since the frequency must increase with increasing resolution. Figure 4 illustrates the tradeoffs that are discussed in detail in subsequent sections. The overall results are summarized in Figure 6. The discussion in this paper excludes torque coupling and power requirements. Those are dependent on many other factors such as Q, actuator type and geometry, gap spacing, and need to be discussed separately.

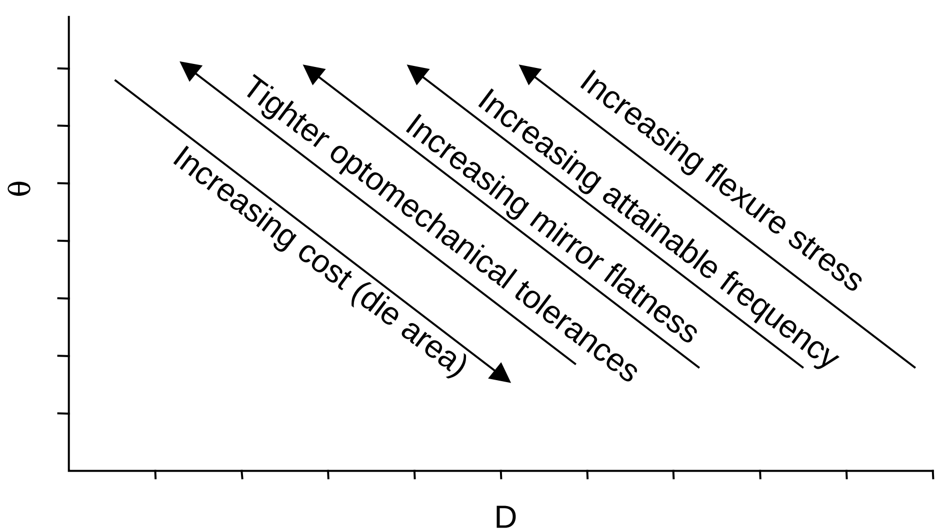


Figure 4: Mirror size and scan angle tradeoffs. More detailed evaluation of general tradeoffs is shown in Figure 6.

3. SCANNER RESOLUTION

The fundamental equation relating mirror parameters to the scan resolution N is given by:[6]

$$N = \frac{4\theta D}{a\lambda}\ , \tag{1}$$

where a is the shape factor of the mirror (a=1 for square/rectangular) and λ is the wavelength of light being scanned. N is the number of resolvable spots and θ refers to θ_{MMSA}. Table below shows minimum θD requirements for different display formats.

Table 1: Minimum θD requirements for various display formats assuming λ=635 nm and *a*=1.

	VGA	SVGA	SXGA	HDTV
N - Horizontal resolution	640	800	1280	1920
θD (deg.mm)	5.82	7.28	11.64	17.46

The equation above shows that resolution increases as the product of θ and D for a given wavelength. Scan resolution changes inversely with wavelength. For multicolor systems, the longest wavelength or a weighted-average of the system wavelengths can be used in the above equation. This equation holds regardless of the scanner material or mode of operation. For bi-axial scanners, this equation can be used independently for each axis. The spot size is usually circular, therefore, the mirror size in the vertical direction should be about the same as the horizontal mirror size. θD is thus the primary value to specify for scanner resolution. It should be noted that θD refers to the mechanical half angle (MMSA), not optical angle. Use of the mechanical angle decouples the scanner design from the optical system design and allows easy translation into flexure stress numbers.

Required horizontal scanner frequency is proportional to the refresh rate of the display system (typically 60 Hz) and the vertical resolution. More than one beam can be bounced off the scanner to scan multiple lines simultaneously. Multibeam scanning can increase the vertical resolution of the system and divides the required scanner frequency down by the number of beams.[7]

4. OPTICS LIMITATIONS AND DYNAMIC MIRROR DEFORMATION

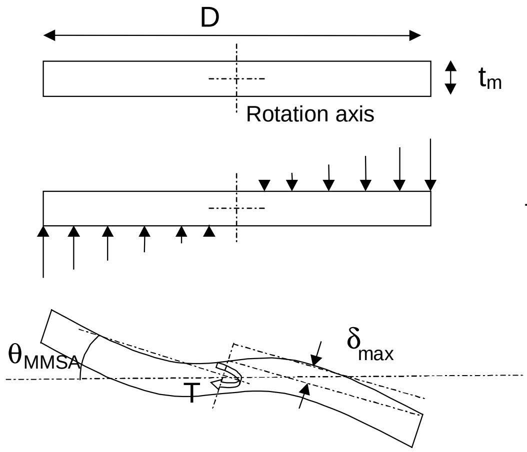
Optical and mechanical design of the scanner housing imposes additional constraints in scanner design. Manufacturing and alignment tolerances become very tight for small scan mirrors. Small mirrors require large scan angles, and large scan angles result in focus errors and non-flat image plane (i.e., field curvature). Field curvature can be corrected optically, but for low cost and low weight head-mounted display applications, there is no room for field correction lenses. All this imposes a lower bound on the scanning mirror size.

Both static flatness and dynamic flatness of the scanning mirror are important for image quality. As illustrated in Figure 5(a), high acceleration forces during mechanical deflection of the mirror result in bending of the mirror. Even very small amount of deviation from linearity due to mechanical deformation can result in optical distortion of the pixel and the image. Maximum deformation occurs at the extremities of the scan. For rectangular block mirrors, the following formulas[8,9] can be used to compute mirror deformation, which is defined as the deviation from linearity as shown in Figure 5(a):

$$\delta(u) = \delta_{\max}(u^5 - 10u^3 + 20u^2 - 11u)/1.83 \tag{2}$$

$$\delta_{\max} = 0.217\,\frac{\rho f^2 D^5 \theta_{MMSA}}{E t_m^2} \tag{3}$$

u = normalized mirror surface coordinate perpendicular to rotation axis
ρ = material density
E = modulus of elasticity (Young’s modulus)
f = scanner frequency



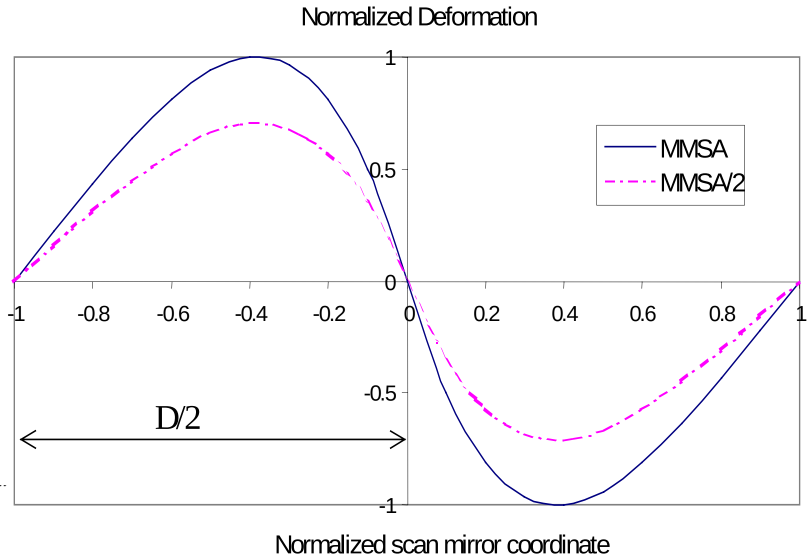


Figure 5: (a) Dynamic mirror deformation graphical representation, (b) surface profile as a result of deformation. Maximum deviation from linearity attained at about 40% of the way from center to the edge of the scanner.

Figure 5(b) shows the shape the mirror surface takes as a function of u (u = ±1 correspond to edges of the mirror). As seen from the figure, the deformation is symmetrical with respect to the center of the mirror. For the kind of aberration the mirror introduces, the maximum mirror deformation (δ_{max}) should not exceed $\lambda/10$ of the shortest system wavelength for the spot to remain diffraction limited across the scan line. Note that δ_{max} is proportional to $D^5\theta$. If system performance is deformation limited, significant gains can be attained by slightly reducing the mirror size.

5. RESONANT FREQUENCY AND FLEXURE STRESS

The fundamental frequency of the torsional oscillator shown in Figure 3 is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{K_f}{I_m}} \tag{4}$$

The flexure stiffness K_f (neglecting stiffness of mirror) and mass moment of inertia I_m (neglecting mass of flexures) are given by[10]:

$$K_f = \frac{2K_s G a b^3}{L_f}\ , \tag{5}$$

$$I_m = \frac{1}{12}\rho t_m L_m D^3 \ ,$$
$$I_m = \frac{1}{12}\rho t_m D^4 \quad \text{for } L_m = D \tag{6}$$

$$K_s = 5.33 - 3.36\frac{b}{a}\left(1 - \frac{b^4}{12a^4}\right) \quad \text{for } a \geq b\ , \tag{7}$$

where G is the material modulus of rigidity and K_s is the flexure shape constant.[10] Required scanner frequency is determined by system design, display resolution, and refresh rate. Note that the resonant frequency of the scanner depends on both mirror dimensions and flexure dimensions, but is independent of scan angle. Resonant frequency of the scanner with a given mirror size can be changed by adjusting the flexure dimensions and mirror thickness within a certain range. Frequency goes down rapidly with increasing mirror size. Assuming flexure aspect ratio (b/a) is kept constant, the following relationship can be used to scale the scanner dimensions without changing its resonant frequency,

$$\frac{b^4}{D^4 t_m L_f} = \text{constant} \cdot \tag{8}$$

High resonant frequencies are more easily achieved with small mirrors and thick flexures.

Another consideration is the stress on flexures. The maximum stress in a rectangular cross-section torsional flexure is given by:[10]

$$\tau_{MAX} = \frac{3K_S G b \theta_{MMSA}}{8L_f} \cdot \left[1 + 0.6095\left(\frac{b}{a}\right) + 0.8865\left(\frac{b}{a}\right)^2 - 1.8023\left(\frac{b}{a}\right)^3 + 0.91\left(\frac{b}{a}\right)^4 \right] \qquad \text{for } a \geq b \tag{9}$$

For reasonable values of flexures dimensions (0.4<(b/a)<1), the following approximate formula can be used for maximum stress

$$\tau_{\max} = \frac{3Gb\theta_{MMSA}}{8L_f}(6.5 - 3.11\frac{b}{a}) \qquad \text{for } a \geq b \tag{10}$$

Choice of the material affects the tolerable stress levels and frequency. Maximum scan angle can be determined by setting τ_{max} equal to some fraction of the yield strength of the material.

It should be noted that this stress is a function of θ, b, and L_f and not of frequency or D. The values for L_f, *a*, and b can be optimized by simultaneously solving equations (8) and (10). Stress can be reduced by increasing L_f or by decreasing *a* and *b*. However, flexure dimensions can only be changed in a limited range. Longer flexures lead to larger package size and higher energy coupling into other oscillation modes, which lowers the system power efficiency and degrades the optical performance of the scanner. Therefore, limitations on flexure dimensions and material strength impose an upper bound on scan angle (denoted as θ_{max} in Figure 6). In addition, while large mirrors require thick flexures for high frequency operation, these thick flexures break at a lower scan angle. Therefore, frequency requirements and limitations on flexure length impose an upper bound on mirror size (denoted as D_{max} in Figure 6). Scanners that are smaller than D_{max} can be designed by changing flexure dimensions without exceeding material stress limits.

6. SUMMARY: CHOOSING MIRROR SIZE AND SCAN ANGLE

Table 2 shows different performance measures and limitations in scanner design. As shown in the table below, it is hard to decouple any of the performance indicators from others. They are all interrelated. There is no single variable in the table that impacts only one of the performance indicators. Highest resolution is obtained by the optimal choice of all variables.

Table 2: Scanner performance indicators and associated design variables

	θ	D	t_m	a,b	L_f	λ	Material
Resolution	x	x				x	
Frequency		x	x	x	x		x
Mirror deformation upper limit	x	x	x			x	x
Flexure stress upper limit	x			x	x		x
Optical and mechanical design limits	x	x				x	
Cost and package size		x			x		x

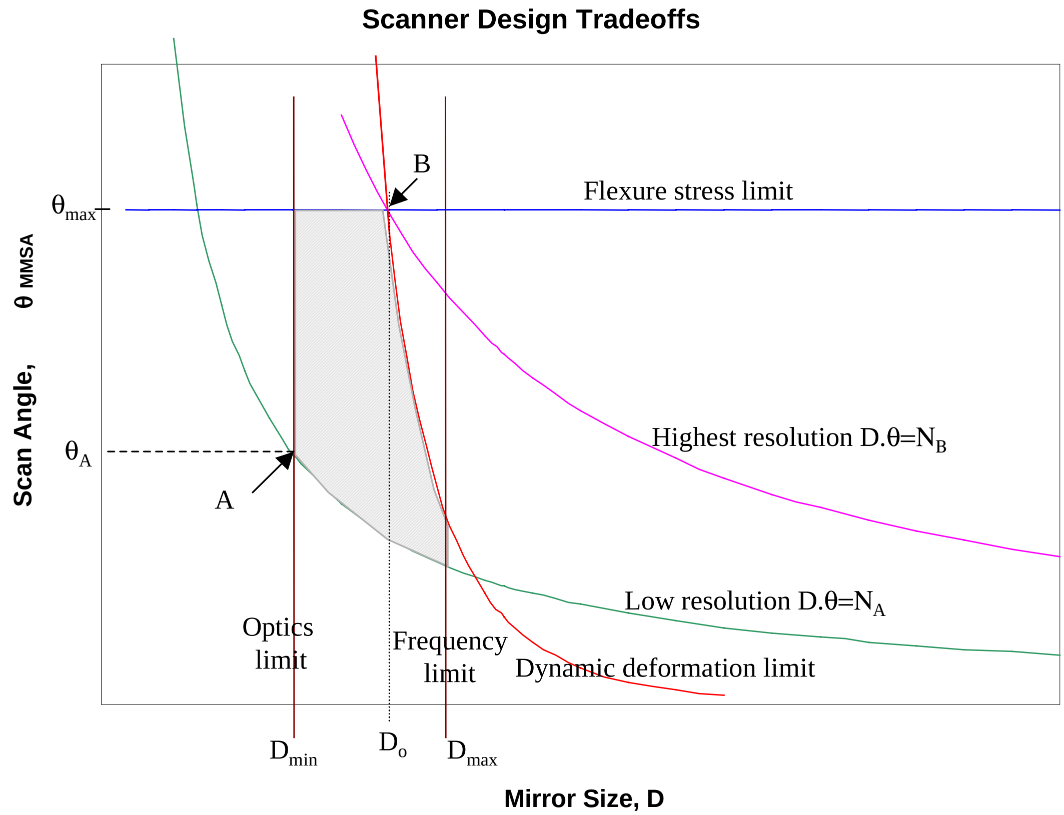


Figure 6: Resolution, flexure stress, and dynamic mirror deformation tradeoffs for scanning display design. The optimal choices of scanning mirror size and scan angle depends on all these tradeoffs.

Scan mirror size, scan angle, and material are the most important design parameters in scanner design for display systems (this is also apparent from the table). Figure 6 summarizes the tradeoffs we discussed throughout the paper. Note that the figure is a 2-D slice from a multidimensional design space. All curves except the resolution curves are influenced by the actual choice of flexure dimensions and mirror thickness. All these variables need to be interactively adjusted to tune the frequency of the system to the desired value.

As discussed before, there is a limit to the range where the flexure dimensions can be adjusted. This limit in turn imposes an upper limit on mirror size D_{max} and an upper limit on scan angle θ_{max}. Scan angles exceeding θ_{max} result in permanent changes in material properties and eventually cause the flexures to break. θ and D values should be chosen below the dynamic deformation limit curve and above the desired resolution curve.

Operating points A and B are chosen from the figure for two different systems with resolutions N_A and N_B. For the low the resolution system, θ and D can be chosen anywhere within the shaded area in the figure. From cost and packaging point of view, D should be as small as optics design and tolerances in the system permits. Point A in the figure shows the best operating point for this system. This system then has the lowest cost, smallest deformation, and lowest amount of stress in the flexures. At the expense of drive power, the same scanner can be operated at scan angles larger than θ_A (but smaller than θ_{max}) to improve the display contrast. The contrast enhancement can be achieved by adjusting system design parameters such as overlap between pixels and spot profile.[11]

The highest resolution can be attained at Point B by balancing mirror deformation and flexure stress. There is roughly a factor of 3 difference in between N_A and N_B in the figure. Such a range in Dθ is enough to cover a broad range of display applications from VGA (640 horizontal pixels) to HDTV (1920 horizontal pixels). Another important advantage of scanning display systems is that a good scanner design that provides high resolution can also be used at lower resolutions by small modifications. First number of parallel scan beams need to be adjusted to bring the scanner frequency to the accessible range of frequencies, then scanner frequency can be fine tuned to the desired frequency by changing the flexure dimensions.

In summary, there is a large design space that allows the standard display resolution levels to be achieved using miniature resonant scanners.

ACKNOWLEDGMENTS

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