# Imaging with laser scanners

*By Leo Beiser*

Electronic image analysis and synthesis entails the sampling of a real or computer-generated image to derive an equivalent electrical signal, and after logical manipulation, reconstructing the image for visual interpretation. The input process is called scanning (or digitizing, if digitized) and the output one, recording, printing, or display.

While several alternate techniques exist, laser scanning and recording has matured for more than two decades, sustaining the prominent posture of providing both high resolution and high speed in a single operation. Usually, the entire image space is addressed with a single raster, to avoid the generation and merging of sub-rasters.

The simultaneous achievement of resolution and speed challenges all imaging technologies—evidence the basic limitations of photographic and video detection processes. Implicit criteria are wide dynamic range, good signal-to-noise ratio during short sampling intervals, and general freedom from artifacts. Laser imaging derives copious pure signal power to override systematic (detection) noise, and the deflecting system accommodates with rapid and well-resolved beam positioning.

In scanning technology, resolution is quantified as the number of elemental points sampled in a single line, and speed is represented by the elemental sampling rate. At the analog level of convolution of a point spread function across an image space, the sampling rate is expressed as the bandwidth, where the two closest successive intensity levels of interest form one (line pair) cycle of limiting bandwidth, in cycles per second. Since scanning is often digitized into elements identified as pixels, the bandwidth is often expressed as the number of pixels per second—usually as Mpixels/sec.

Quite remarkably, the single discipline of laser scanning has encompassed the widest range of image resolutions and speeds. During the first of two decades, attention concentrated upon the highest performance systems, such as for reconnaissance and graphic arts scanning and reproduction. Soon, however, the more moderate image requirements of business graphics and later the lower resolutions and speeds of such systems as bar-code reading became dominated by this technology.

Having effectively divided the field into three categories, high medium, and low, we quantify them further in terms of resolution and bandwidth, to allow assignment of specific scanning techniques to their appropriate tasks. In formulating a scale of relative performance, this in no way moderates the effort dedicated to creating a system which falls into the lower categories. The task of optimizing a design to match its requirements remains a challenge for all levels of performance. These levels are characterized in Table I.

While higher and lower performance levels than those identified do exist and can be accommodated, the range of resolutions from 500 to 50,000 elements/scan and speeds to 50 Mpixels/sec identifies the major gamut. And, while some laser scanning techniques can be designed to serve any portion of this range, others are more appropriate for limited tasks, subsequently expressed.

Other important parameters are accuracy, linearity, random access capability, adaptation complexity, and cost. Also critical are the associated electro-optical processes which form a system: optical signal detection for scanning and op-

LEO BEISER is president and research director of Leo Beiser Inc., a consulting and research company in Flushing, N.Y. He is also an adjunct professor at Polytechnic Institute of New York, Institute of Imaging Sciences.

*TABLE I. Characterization of scanner performance*

| Category | Resolution, N Elements/Scan | Speed; BW Mpixels/Sec. | Typical Systems |
|---|---|---|---|
| High | >10,000<br><50,000 | >20<br><50 | Graphic Arts<br>Reconnaissance<br>Quality Control |
| Medium | >2,000<br><10,000 | >2<br><20 | Business Graphics<br>Image Analysis |
| Low | >500<br><2,000 | <10 | Video<br>Medical<br>Bar Code |

tical modulation, and media for recording and display. Finally noteworthy is the ability to conduct laser input and output processes over a wide spectrum of color or "non-color"—UV through IR. We now concentrate upon the dynamic process of scanning and its unique burdens of design integrity.

Four principal techniques have been selected for discussion:

- the rotating polygon,
- the acoustooptic deflector,
- the galvanometer, and
- the holographic deflector.

The galvanometer, in this context, includes the broadband and resonant types. Other techniques, such as electrooptic and piezoelectric, are of such infrequent utilization, and translational and drum configurations are so dominated by precision mechanics that these options, although sometimes very significant, fall beyond typical deflector interests.

## Laser scanned resolution

Since resolution dominates image information handling, its fundamentals in laser scanning merit expression. With resolution defined as the number of $N$ spots within the scan line, clearly the smaller the spot and/or the longer the line, the higher the resolution. However, almost all scanners impart *an angular change* to the laser beam (for high speed—as compared to translation of a lens across an image surface). The beam may be pre-focused, or focused subsequent to scanning by converging it through an appropriate ("flat-field") lens, which transforms the arcuate change to a linear displacement of its focal point.

In all cases, diffraction-limited resolution is determined *at the scanner*, taken as the ratio of the scan angle to the diffractive spread from its aperture. Thus, $N$ is proportional to the size of the deflecting aperture $D$ and the angle $\Theta$ through which it scans. Subsequent passive optical manipulation is conducted with $N(\Theta D)$ invariant (a form of the Lagrange invariant). Thus, deflectors which execute small angles, such as acoustooptic (A-O) devices, need to be provided with a large aperture and require optical transformation to traverse a large-image format. We shall later express further consequence of $N = k \cdot \Theta D$; where $k \approx$ constant.

Implicit in resolution is accuracy and repeatability, for unless the pixel placement is rigorous to a small fraction of a pixel spacing, the image becomes perturbed with characteristics which appear as "noise"—pseudo-random or random, depending upon the character of the errors. When pseudo-random, such as grouped scan lines, visual perception suffers an insidious annoyance far greater than may be represented as information loss alone. Thus, the challenge of high resolution is not only the magnitude of $N$, but the integrity of its elemental positioning over the full image field.

## The rotating polygon

The rotating polygon is the standard against which most deflectors are compared. As one of the earliest scanner configurations, it has survived many challenges, sustaining exemplary performance cost effectively, spanning the full spectrum of resolutions and speeds identified above. More recently, techniques have been developed for overcoming one of its principal limitations: that of providing accurately oriented facets.

Although the most familiar polygon configuration is prismatic (facet planes parallel to the rotating axis), important utility exists for the pyramidal form (facet forming a regular pyramid about the axis). Also, while almost all rotating polygons operate with reflective facets, a small fraction may be found operating in transmission, displacing the beam via parallel plate refraction. The prismatic polygon is usually illuminated in a plane normal to the axis (see Fig. 1), such that the output beam angle is double the rotating angle, while the pyramidal polygon is usually illuminated coaxially, such that the output angle is equal to the rotation angle. Rotational errors exhibit a corresponding 2:1 variation.

The fabrication cost is determined most by the angular accuracies, with special attention devoted to the "pyramidal error"—the departure from uniformity of the facet angles with respect to the axis. As illustrated in Fig. 1, this error creates the misplacement of scan lines in the cross-scan or "vertical" direction. A method of reducing this error significantly entails the use of anamorphic beam handling, whereby the illumination incident upon the facet is narrowed in the cross-scan direction only (see Fig. 2) and then restored to its normal subtense after deflection. Let us clarify this important process.

With resolution proportional to the product of $\Theta$ and $D$, assign $N_x = k \cdot \Theta_x D_x$ as the desired "horizontal" resolution, and in quadrature, $N_y = k \cdot \Theta_y D_y$ as the cross-scan error component. (Note: A *desired* vertical deflection may be independently generated by a dedicated vertical scanner, or by translating the medium uniformly in the cross-scan direction). Since the horizontal deflector is to impart *no* vertical misplacement, we require $N_y \rightarrow O$, whence $\Theta_y D_y \rightarrow O$. But $\Theta_y$ *is the problem*—the "irreducible" angular error of the deflector. The remaining variable for control is $D_y$, the aperture subtense in the error direction. By reducing the illumination on the facet in that direction only (with anamorphic optics) and then restoring the beam to normal after deflection (again with anamorphic optics), the vertical error is reduced by a factor proportional to this reduction ratio.

Various implementations of this process have appeared since its introduction some 13 years ago, by orienting the anamorph (usually a cylindrical lens) into different portions of the optical path, including the flat-field lens. Also, a single anamorph may be utilized in a double-pass arrangement where both input and output beams traverse the same optics. Other techniques of cross-scan error reduction include incremental control of that direction by an independent (small angle) high-speed deflector, such as an A-O device.

## The acoustooptic deflector

Although acoustooptic deflection may appear relatively recent, a remarkably elegant form of such scanning was utilized in the Scophony TV system in 1939. The operating principle is that of controlled diffraction illustrated in Fig. 3, whereby an incident light beam angle is modified by the change in spacing of a (near) linear phase grating operating at or near the Bragg regime.

The grating develops from a (near) periodic variation in index of refraction within a transparent (usually solid) medium, caused by the compressions and rarefactions of an acoustic wave propagating through the material. The grating spacing at the acoustic wavelength is inversely proportional to the excitation frequency. Thus, a variation of the drive frequency through a range $\Delta f$ will vary the spacing and scan the corresponding diffraction angle of the light beam.

Since resolution $N$ is proportional to the change in angle and to the aperture size (and hence to the transit time $\tau$ of the acoustic wave across the aperture), then resolution is proportional to $\tau \Delta f$. More completely, $N = (\tau \Delta f/a)(1 - \tau/T)$, where $a$ is an aperture shape parameter and $T$ is the scan period. The second factor is simply the scan duty cycle, which in the underilluminated polygon is represented by a similar factor $(1 - D/S)$ where $D$ is the illuminated width and $S$ is the full facet width. Resolution is increased with an increase in transit time (larger aperture and/or slower acoustic velocity in the material) and larger acoustic frequency change. A-O deflectors operating in this direct mode are limited (primarily by the available A-O materials) to $N \approx 2000$ elements per scan. They can also function as random-access positioning devices, effectively switching during the $\tau$ required to fill the aperture with a new grating period—hence a new beam position.

An interesting form of A-O deflector seldom encountered, although intensively investigated, is the traveling lens or chirp system, in which a tandem arrangement of two deflectors cooperate to enhance resolution. The second of the two is the principal component, with special demands made upon its fabrication and electrical drive. A pulse of frequency-modulated acoustic energy is generated at one end of its long subtense—about as long as the image width! This pulse is chirped; shaped to exhibit diffractive characteristics analogous to a positive cylindrical lens.

This synthetic lens travels the length of the transducer at the (very fast) acoustic velocity. Near-collimated light projected upon this traveling cylindrical lens (by a prior deflector tracking at synchronous transverse velocity) will be focused thereby in one direction. Then it is focused by a second fixed crossed cylinder in the other direction, to form a relatively small spot scanning across the image subtense. The first scanner is usually another A-O device (as described above), designed to launch

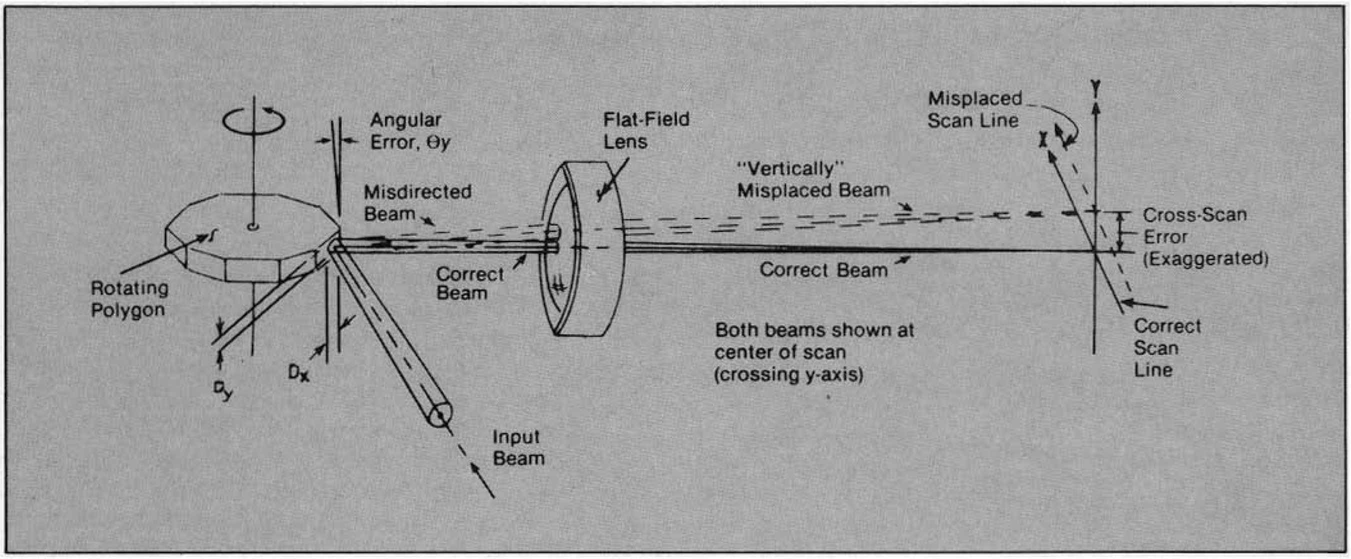


***FIGURE 1. Rotating polygon scanner showing misplacement of scan lines in the y direction.***

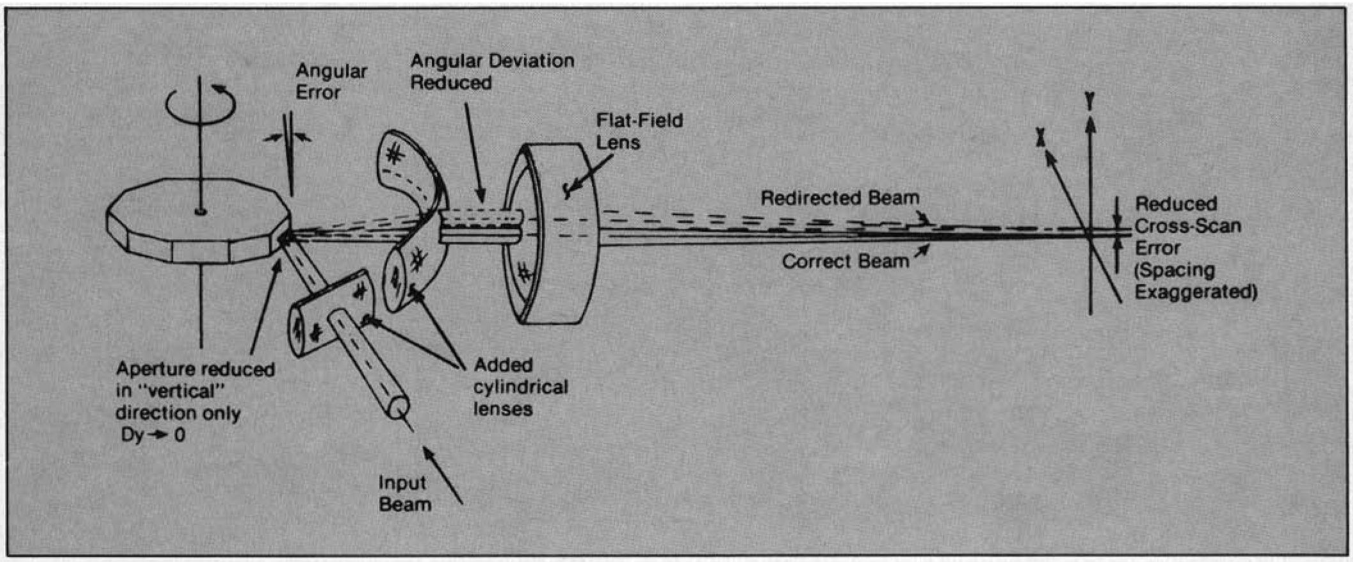


***FIGURE 2. Reduced vertical aperture to reduce cross-scan error in Fig. 1.***

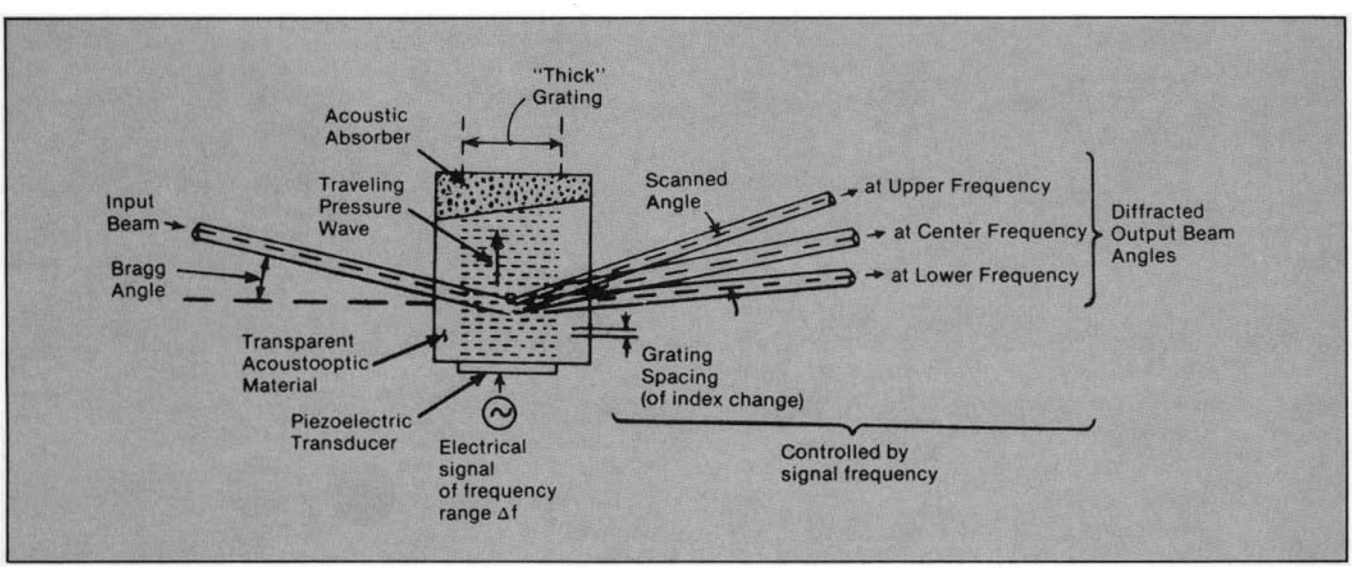


***FIGURE 3. Acoustooptic deflector develops synthetic diffraction grating which varies output beam angles.***

and track lower resolution beams upon the traveling lens.

The resolution gain is approximately equal to the ratio of the distance between the A-O devices to the focal length of the second A-O device. If, for example, the ratio is 10:1, then a 500-element prescanner will be enhanced to a 5000-element output by the traveling lens. Because of its fixed acoustic velocity (which may not correspond to the desired velocity), this technique is no longer random access, and falls into the category of high inertia components, competing with the much simpler rotating polygon. Also, extra anamorphic optics is required to shape the beam for pre-scanning and to provide a near-isotropic scanned spot.

## The galvanometer

The galvanometer derives from the D'Arsonval moving coil motor principle introduced in 1882. When coupled to a mirror, it provides low inertia drive for angular change. For scanning, the original moving coil instruments have been almost superseded by the family of "moving iron" movements, to provide higher torque for larger mirrors. Two distinct classes of galvanometers exist that exhibit radically different performance: the broadband galvanometer and the resonant one, which in some designs utilizes an induction-driven moving coil.

The broadband configuration can provide pseudo-random access, taking advantage of its low inertia. The resonant types are as distinct from the broadband components as the traveling lens A-O device is from the conventional A-O deflector, for in resonance, its position is not controllable randomly, acting more like a high inertia device. It can execute large angular excursions at relatively rapid rates, with precise retracing of recurrent cycles established by the electro-mechanical suspension rather than by the drive signal (which determines primarily the excursion amplitude).

Whereas the broadband device with feedback can be made to execute a very linear ramp (or modification thereof within the electromechanical bandpass), the resonant device will execute only a harmonic (sinusoidal) excursion, albeit quite accurately. In resonant systems where linearity must be provided, the technique of pixel timing by traversal of an auxiliary pilot beam across a linear grating can be used as a reference. Synchronous modulation of illumination intensity is also necessary to compensate for the varying dwell time per pixel, to approach uniform exposure per pixel over its approximate 40% duty cycle (if utilized in one direction only).

The basic conflict in the galvanometer is the need to sustain a low inertia while implementing a rugged and angularly precise movement. To keep inertia low, the armature is small and its suspension short. Viewing a stable electric motor as a prototype, angular errors are constrained with a long rigid shaft suspended between precise and sturdy bearings. In the galvanometer, this can be implemented only to a very limited extent without overburdening its inertia. Thus, achievement of low wobble error in the galvanometer is of fundamental concern.

Although galvanometers can execute relatively large angular excursions with rather large mirrors, the resolution (proportional to the product of $\Theta$ and $D$) can be seriously perturbed by positional uncertainty. Intensive work in application of electrical positional feedback and optimization of bearing structures has stretched the galvanometer performance significantly. Caution need be exercised, however, in demanding more than a few thousand elements of resolution per scan. With great dedication to these factors, the resonant galvanometers can provide several thousands of elements of resolution at fixed speed. While benefiting from freedom from multielement nonuniformity, it operates at low duty cycle and often requires timing linearization and intensity normalization.

## The holographic scanner

As the prior three cornerstones of scanning components were shown to be available over a substantive period of time, so, perhaps suprisingly, is holographic scanning. Introduced over 18 years ago, some of the important factors relating to holographic scanning and its boundary conditions were then well expressed. A series of intensive investigations followed, yielding families of variations in substrate geometry and illumination/reillumination technology, culminating in dramatic performance achievement. In fact, the highest performance ever recorded for *any* optical scanner was that from the Holofacet scanner, invented by the author in 1969 and tested in 1972 to provide 20,000 elements/scan at 200 Mpixels/sec. This apparatus is now in the permanent collection of the Smithsonian Institution.

The prototype for a holographic scanner is the rotating polygon; in particular, the pyramidal one. Similar requirements for illumination symmetry hold true, to sustain high performance throughout the entire scan angle. The principle may be simply expressed: replace the facets of a conventional polygon with gratings such that upon reillumination of the gratings, the

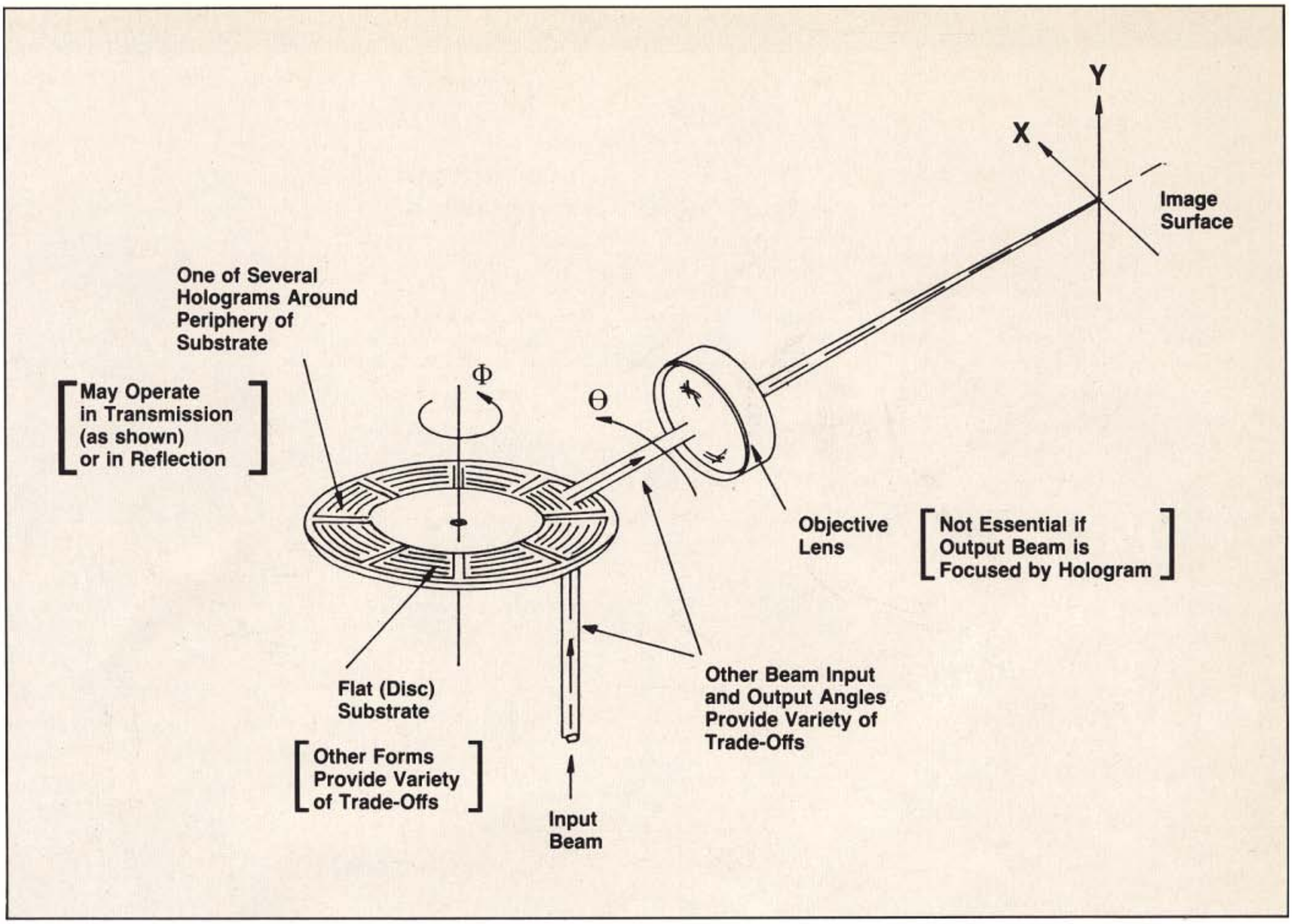


***FIGURE 4. Diffracted output beam rotates through angle Θ related to grating rotation angle Φ.***

diffracted output beam position bears a direct relationship to the angular change of the substrate (see Fig. 4.).

The intent is to eliminate the need for precise machining of facets, reduce aerodynamic loading and noise by eliminating the facets, allow for replication by pressing or re-exposure, create a low mass system, allow use of wobble reduction techniques, and allow generally for lower cost fabrication and utilization (such as with lower tolerance bearings).

However, some holographic scanners exhibit a few very serious complications. Among the most important are the consequences of wavelength shift between holographic exposure and reillumination, and the generation of an unbowed scan line on a flat surface. Since the output beam angle is governed by diffraction, it is wavelength-sensitive, and reconstruction at a wavelength other than that used for construction will not only modify the output angle, but could (if the hologram exhibits optical power) introduce wavefront aberration.

Also, since a perfectly unbowed scan line is derived from an output beam that is typically normal to the rotating axis, and the output beam launched by disc-like devices are uniquely nonnormal, this factor merits special attention. While normal output beams are available readily from other substrate geometries, substantial work has been conducted with considerable success in approximating a straight-line image from disclike configuration.

With growing attention devoted to these problems, and with significant technology adaptable from polygon scanning (such as anamorphic beam handling), we expect that operational holographic scanners will appear—not only in the relatively noncritical point-of-sale applications now operative, but in higher resolution imaging fields.

## Performance comparison

Characteristics of the four principal scanner types are expressed in the accompanying comparison chart, Table II. Among the parameters represented, *scan angle* is listed separately, for, along with its contribution to resolution, extremely narrow angles often require extra optical expansion to cover the image space—as by the A-O deflector. *Resolution* is considered near diffraction-limited. Aberration beyond one-half wave is seldom justified nor tolerated in laser scan systems. *Scan rate,* when coupled with *Resolution,* can be considered as a merit factor, for their product represents the bandwidth. The Polygon and Holographic scanners are capable of

*TABLE II. Scanner Characteristics*

| Type | Optical Technique | Random Access | Scan Angle | Resolution Elements per Scan | Scan Rate (per second) | Accuracy and Linearity | Cost | Comments |
|---|---|---|---|---|---|---|---|---|
| Polygon | Reflective (Some Transmissive) | No | Wide (Per No. of Facets) | >5,000<br>>50,000 Over-illuminated | >10,000 | Very High; Critical Repeatability | High, Prototype;<br>Moderate-Low Production | Highest Production Performance |
| Acousto-optic | Diffractive<br>(Transmissive) | Yes<br>No, Traveling Lens | Narrow<br>(Expand Optically) | <2,000<br>>5,000 Traveling Lens | >10,000 | Very High (Electronic Drive) | Moderate<br>High, Traveling Lens | Associated Optics & Electronics<br>Sub-Raster Capability |
| Galvanometer | Reflective | Yes, Broadband<br>No, Resonant | Moderate | >2,000<br>>10,000 Special Resonant | >1,000<br>Resonant, Higher | Moderate (Feedback Improvement) | Moderate-Low | Associated Electronics<br>Sub-Raster Capability |
| Holographic | Diffractive<br>(Reflective or Transmissive) | No | Wide (Per No. of Facets) | >5,000<br>>50,000 Over-illuminated | >10,000 | Very High;<br>Potentially Less Critical than Polygon | High, Prototype;<br>Moderate; Production | Highest Performance Tested<br>Maturing Technology |

data rates in the hundreds of Mpixels/sec. At extremely high rates, the holographic scanner has the advantage, because of its aerodynamic stability.

*Accuracy* and *linearity* contend with systematic errors: optical, mechanical, and electrical. The high-inertia systems are capable of superb angular uniformities. Ball bearings can provide accuracies to greater than 1 part in 100,000 elements; gas bearings to 1 part per million elements, depending upon scan angle. The larger the better with regard to fixed bearing noise. Systems that establish timing from pilot beam traversing reference gratings are less dependent upon inertia. This is exemplified by the galvanometer, for its intrinsic accuracy may be to 1 part in 20,000 over a limited scan angle. If a 10% pixel placement error is tolerated, this represents 2,000 elements at high integrity.

The linearity and repeatability of acoustooptic scanners is almost entirely dependent upon the drive signals and can provide performance consistent with good electronic design. One commanding advantage of both galvanometer and A-O deflectors is their freedom from multielement inconsistencies. This is not only valued in the along-scan direction, but is a dominant factor in the cross-scan direction, where minute differentials in beam positioning can form an insidious error in line spacing uniformity.

Costs vary widely, not only between different systems, but among them. The only rational correlation to cost is that of performance in resolution, speed, and uniformity. While the scanners may be similar in cost for similar performance, particularly with new machining and replication techniques for fabricating polygons and mirrors, the supporting and auxiliary equipment can render a major cost impact. For example, a complex flat-field lens with anamorphic correction or a multichannel modulator with complex electronic programming can cost significantly more than the basic scanner component.

Each application merits unique consideration. There is no preferred approach. The factors expressed in this brief review provide a basis for detailed analysis and design, to reveal optimizations utilizing different techniques for different tasks.