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The Laser Printer

Introduction

Next to the diode laser used in compact disc players, the most commercially exploited application of the laser is probably the laser printer. In designing such a product a large number of factors come into play, some technology driven and others market driven. There is little point in manufacturing a printer which is so expensive no-one will buy it. Similarly a printer which offers poor reliability and resolution will be difficult to place in a competitive market. Engineers must be aware of and give due regard to the trade-offs involved in the development of such products and to avoid focusing on purely technical issues.

Basic Principles

Shown in Figure 1 is a simple diagram of a laser printer. The light beam from the laser, proceeds through a modulator, which impresses the data onto the beam in the form of intensity variations. Note that for the purposes of this discussion the intensity information is binary (1s or 0s) as opposed to analogue. For other purposes, analogue-intensity modulation is of course also possible. The modulated beam then passes to the deflector, which scans the beam across the photosensitive media. In most laser scan systems some form of scan detection is necessary in order to synchronise the scan beam with the data stream. Although this figure is simplistic, we shall use this as a basic model for the printer system and examine each of the component technologies in the following sections.

There are six steps in producing a printed page with a laser printer :

1. Generating the Laser Pattern

The laser beam is reflected from the surface of a rotating polygonal mirror. This scans the beam along the axis of the photoconductive drum (X direction). Rotation of the drum moves the scan down the surface of the photoconductor in the Y direction. The result is a raster scan of the drum surface.

When an external modulator such as an acousto-optic modulator is used, this will, in response to a digital signal, deflect the beam either into the optical path to the drum or away from it, in effect turning the beam on and off. By appropriately timing when the beam is turned on, the character or image to be printed can be projected onto the drum as the laser beam scans its surface.

2. Forming an Electrostatic Image from the Laser Pattern

The drum used in the laser printer is a photoconductive sandwich applied to an aluminium cylinder. The sandwich consists of an aluminium layer on which there is a cadmium-sulphide photo-conductive layer. Outside the CdS is an insulating polyester layer.

Figure 2 shows how the drum is used in the laser printer. The elements used for forming the electrostatic image are the positive charging corona, the ac simultaneous discharging corona, the laser beam, and the overall illumination stage.

At the charging corona (A), positive ions are produced, charging the surface of the drum. After passing this corona the potential of the drum surface is about 13000 volts.

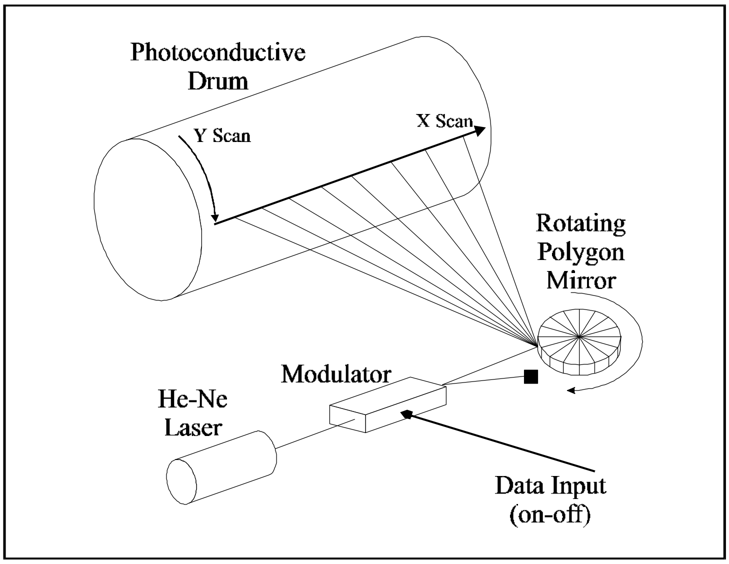

Figure 1: Laser raster-scan system

At B, a negatively biased simultaneous ac corona discharger tends to drive the drum surface to zero volts. At the same point, the modulated laser beam impinges on the drum. When the laser beam is on, the CdS region struck by the beam is made conductive, and the voltage throughout the sandwich is zero. In areas where the laser beam is off, the voltage inside the sandwich is several hundred volts negative even though the surface potential is zero.

By applying an overall illumination (C), this internal voltage difference is converted to a surface voltage. The laser-exposed areas remain at zero volts, while those areas not exposed to the laser change to approximately +500 volts.

Following the image formation process, the potentials of both laser exposed and non-exposed areas are measured with a non-contacting electrostatic voltmeter and compared with target values. The machine-control processor adjusts the appropriate parameters to keep the potentials at the target levels.

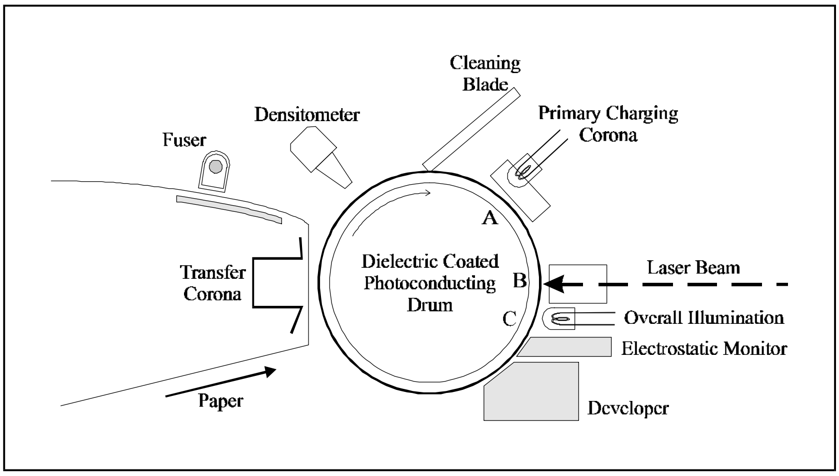

Figure 2 : The Printing Process

3. Development of the Imaged Areas

The surface of the drum now enters the development section with exposed areas (approximately zero volts) and non-exposed areas (approximately +500 volts). The developer station contains a mixture of small black plastic particles known as toner along with larger iron-based particles known as carrier. This toner is transported to the drum on a magnetic brush which generates a toner cloud at the drum surface. The toner is charged in such a way that it is attracted to the portions of the drum near zero volts and is not attracted to the portions of the drum surface with a high positive potential. There is now a visible image on the surface of the drum, with toner in the areas that were exposed by the laser beam.

Control of the development parameters is accomplished by measuring the developed density (blackness) of a pattern printed on an area of the drum that does not contact the paper in the transfer process. This developed density is measured at the reflective densitometer shown in Figure 2. The measured density is compared with the target density by the machine control processor, which then adjusts the appropriate development parameters to maintain the proper density.

4. Transfer of the Image to Paper

The transfer process is simply a way of transferring the toner from the drum to the paper. The positively charged toner is attracted to the paper by applying a negative charge to the paper. This is done by a negative corona behind the paper.

5. Fixing the Toner to the Paper

After transfer the toner appears on the paper surface as small particles. To hold the toner in place permanently, it is necessary to melt it into the paper. The toner used is a carefully chosen thermoplastic that has a well controlled melting point. The printer uses a non-contacting radiant fusing system along with a preheating area to assure reliable and effective fusing.

6. Cleaning the Toner off the Drum

Following transfer the small amount of toner that remains on the drum must be removed. The machine contains a blade made of soft plastic that scrapes loose the toner that has adhered to the drum. A vacuum system removes the toner that piles up in front of the blade. The drum is then ready to begin the next cycle.

Generating the Line Pattern

Generating the pattern for modulating the laser is accomplished by the logic circuits within the printer. The computer sends basic information on what the page to be printed should contain and how it is formatted (for example text and graphics, margin sizes, headers, etc.). The printer then has to decide how these instructions should be translated into directions to the laser and its support hardware. Recall that the page image will be built up line by line and each line consists of the laser beam being scanned horizontally on the page. When the laser is “on” a bright spot will be incident upon the photo-sensitive drum thereby producing a dark spot on the final page. The type of laser used determines the smallest spot size obtainable and hence the printer resolution (number of dots per inch). As we shall see, other factors also come into play in determining this resolution such as the maximum rate of data transfer, the speed at which the modulator can switch and the desired printing speed. The laser can be modulated in two ways: switching the laser power on and off, or use a high speed shutter to modulate a continuous beam.

The Laser

To make the right choice of laser for the printer we must first examine the specifications which need to be met.

The laser should have a long working life span (greater than 20,000 hours operation). In early laser printers hard-sealed HeNe laser where used since at that time diode lasers were notoriously short lived, lasting only a few hundred hours in continuous operation. Diode laser technology has developed very quickly in the last decade or so. Laser diodes now have operating lifetimes comparable to sealed tube gas lasers. Another advantage HeNe lasers had in early printers was their relatively low unit cost. This advantage has, of course, disappeared since the large scale commercialisation of diode laser production, principally for the compact disc market.

The laser should be compact and have low power consumption. Again, diode laser developments have surpassed the HeNe in this criterion. Diodes are now much more compact (by at least an order of magnitude) and the power supplies for these devices not only have very modest power consumption but also have no requirement for high voltage discharges which are necessary in gas lasers.

The output beam quality should be of a high standard with as little as possible astigmatism, and wavefront distortion. This is an area where HeNe lasers probably still have the edge over diode lasers whose output tends to be in the form of an elliptic beam. Optics can be used to correct this and integrated into the diode laser package.

The laser wavelength should be one at which the drum is photosensitive. This is generally at shorter wavelengths and first generation laser diodes were of little use since they operated in the infra-red. Cheap laser diodes are now readily available at wavelengths close to the 633nm of the HeNe laser and indeed are moving to the blue/green region of the spectrum.

Given a specification of the required laser printer resolution, we can calculate the necessary laser power for a desired printing rate.

<u>*Example*</u>

A laser printer has a quoted resolution of 600 dots per inch and a printing rate of 10 A4 pages per minute. If the exposure level required for the particular photosensitive drum used is 1.5μJ / cm^2 at the laser wavelength, what is the minimum laser power necessary?

> We are required to first of all calculate the maximum number of dots per page and, based on the printing rate, the rate at which energy needs to be deposited on the drum for this number of dots.
>
> 600 dots/inch = (600/25.4) dots/mm
>
> we therefore have a dot density of
>
> $$(600/25.4)^2 \text{ dots/mm}^2$$
>
> The area of the page (A4) = 210 x 297 mm^2, giving a maximum number of dots per page of
>
> $$210 \times 297 \times (600/25.4)^2 \text{ dots}$$
>
> A printing rate of 10 pages per minute implies the rate at which we must produce dots is given by
>
> $$10 \times 210 \times 297 \times (600/25.4)^2 \text{ dots/minute}$$
>
> $$= [10 \times 210 \times 297 \times (600/25.4)^2] / 60 \text{ dots/s}$$
>
> $$= 5.8 \times 10^6 \text{ dots per second}$$
>
> To calculate the exposure required per dot we first calculate the size of each dot based on the dot density. We assume the dots are evenly spaced.
>
> $$\begin{aligned} & (600/25.4) \text{ dots/mm} \\ \Rightarrow \text{dot size} \quad & = (25.4/600) \text{ mm} \\ & = 42\ \mu\text{m in diameter} \\ \Rightarrow \text{dot area} \quad & = 1764\ \mu\text{m}^2 \end{aligned}$$
>
> Exposure level is 1.5 μJ/cm^2 = 1.5 x 10^{-8} μJ/μm^2

Hence exposure per dot = $(1.5 \times 10^{-8}\ \mu J/\mu m^2) \times (1764\ \mu m^2)$
$= 2.65 \times 10^{-5}\ \mu J$

Hence the laser power level necessary for this specification is
$(2.65 \times 10^{-5}\ \mu J) \times (5.8 \times 10^{6}\ s^{-1})$
$= 153.5\ \mu W$
$\approx 0.1 mW$

This sort of power level is easily obtainable for modern diode and HeNe lasers.

Note the we have not allowed for the optical losses which occur in the lenses and mirrors used to image the laser to a spot, but given the modest power requirements calculated above in a real laser printer we would be able to specify a laser power up to few 10's of mW. A more serious concern is the data transfer rates needed since a dot rate of 6×10^6 dots/s is roughly equivalent to data rates of around 0.75Mb/s.

In choosing the laser one must also give consideration to how the laser will be modulated. For diode lasers this is simply achieved by modulating the laser driver which can be done at rates greater than MHz. Most laser diode drivers come with at least an input for a modulation signal and some with internal modulation. For HeNe lasers an external modulator is required. This adds the system complexity and cost. However, in early printers this was unavoidable and acousto-optic modulators were employed. In these modulators harmonic acoustic waves travel through a transparent crystal, commonly TeO_2, and the light is diffracted from these waves at an angle which depends on the wave spacing, an hence the acoustic frequency. By changing frequency one can control the angle at which the light is diffracted and so, in switching between two frequencies one can switch the laser into and out of the desired beam path. Alternatives such as electro-optic modulators were not used due to the high voltages used in these devices, their susceptibility to thermal drift effects and the need to work with polarised light.

In summary, the technical evolution of the diode laser has meant that it has now become the obvious choice over the once standard HeNe laser in terms of cost, size and convenience.

The Line Scanner

A basic deflector is shown in Figure 3. In this diagram the width of the deflected beam at the deflector is W and the angle of deflection is Ψ. One can define a deflector merit function M by the relation,

$$M = W\Psi$$

Since the minimum angular resolution α of a uniformly illuminated circular aperture is given by the relation,

$$a = \frac{1.22\, l}{W}$$

we can derive the number of resolvable elements N, that the deflector is capable of producing by combining the above two equations so that,

$$N_r = \frac{\Psi}{a}$$

or

$$N_r = \frac{M}{1.22\,l}$$

These equations assume that the deflecting aperture is circular and uniformly illuminated and that the spot is diffraction limited by the system exit pupil.

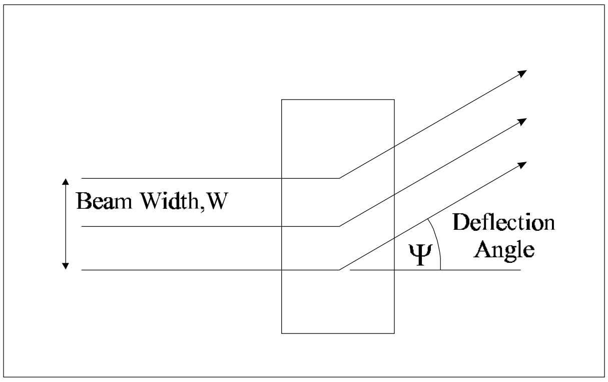

Figure 3 : Basic Deflector Diagram

Polygonal Scanners

As shown in Figure 1, the polygonal scanner is composed of a multifaceted mirror, which is usually in the form of a “disk” configuration, a driving motor that can be electrical or air driven, and a control system to power the motor and control its speed as necessary. The driving circuitry can be quite simple and will not be discussed.

The available scan angle from a polygonal mirror of K facets can be shown to be,

$$q = \frac{(2)(360)}{K}\,\text{deg}$$

This is so since the mirrors are on the circumference of a circle and if there are K mirrors, then each mirror must subtend 360/K degrees from the centre of rotation. This equation does not apply when K has a value of 1 or 2 for obvious reasons. Furthermore, the scan angle is doubled by reflection as in galvanometers, giving 720/K as the scan angle per facet.

The minimum resolvable angle α can be used to derive N, for a polygonal scanner of K facets and facet width W. For a Gaussian beam, the relation,

$$N_r = 12.6\frac{W}{lK}$$

can be derived. For W = 1 cm, K = 24, and λ=633nm yields,

N_r = 8294 spots.

The merit function M, can be shown to be

$$M = 12.6\frac{W}{K}$$

Substituting the above values into this equation the merit function is found to be,

$$M = 12.6 \times \frac{10}{24} = 5.24\text{mm}$$

If we wish to make 6000 scans/sec from this device we need only spin the polygon at 6000/24 or 150 revs/sec. This is only 15000 rpm, which is not a stress on either the motor or the polygon. This scanner also produces ~8300 spots/scan. If we increase the number of facets to 36, the number of resolvable spots is ~3700 if the polygon diameter is kept approximately constant, and the required rpm now reduces to 10,000, which is easier to achieve. For a reasonably large number of facets K the polygon diameter D is

$$D = \frac{WK}{p}$$

Thus a 36-facet polygon having 6.67 mm facets is only 76 mm in diameter.

Until recently, there has been a severe problem with polygonal scanners that limited their volume producibility and cost effectiveness. This problem is the requirement of facet-to-facet angular uniformities. Assuming we wish to scan an 11in. page with our 36-facet scanner, the system geometry requires a polygon-to-scan plane distance of ~31 in.. With the facet width W of 6.67 mm and a 31-in. or 787mm polygon-to-scan plane distance D, the system F/# or focal ratio is,

$$F/\# = \frac{787}{6.67} = 118$$

If now we consider the facet to truncate the imaging beam so that it is uniformly illuminated, we can approximate the scan-spot size *d* as

$$d = 1.22\ \lambda\ (F/\#)$$

This equation is not strictly correct, since, due to the rectangular facet geometry, the spot size is really determined by a sinc^2 function rather than the square of a first-order Bessel function. The spot-size differences are minimal, however, and for the purposes of this discussion precise determination is not necessary. For λ=633 nm, d = 91µm at the 50% intensity points of the spot.

If we assume that we can tolerate a spot-position error of 1/2 spot diameter at the 50% points, the allowable facet-to-facet angular error δ can be described as,

$$d = \frac{0.61 l\ (F/\#)}{D}$$

or

$$\delta = 58\ \mu\text{rad} \quad \text{or} \quad 12\ \text{arc-sec}$$

This angular error is the actual error that can be tolerated and since angles are doubled upon reflection from our mirrors, then δ must be halved to obtain the facet-to-facet tolerance value. This means that we can tolerate only ~6 arc-sec error between any two facets. This is difficult tolerance to achieve in production situations. Tolerances much tighter than this can be achieved in special devices, of course, but an actual commercial product cannot tolerate components costing many thousands of dollars each.

A technique must therefore be found to reduce the need for such precision fabrication. As shown in Figure 4, a cylindrical lens can be inserted into the optical path of the scanning beam to reduce the facet-to-facet angular tolerances by 50-100 times. This means that the angular tolerances can now be on the order of arc-minutes instead of arc-seconds, and the problem is sufficiently corrected to permit low-cost polygonal scanners to be used. It should be carefully noted by the reader that only polygon facet angular errors that produce ray deviations from the scan plane are corrected by the above technique.

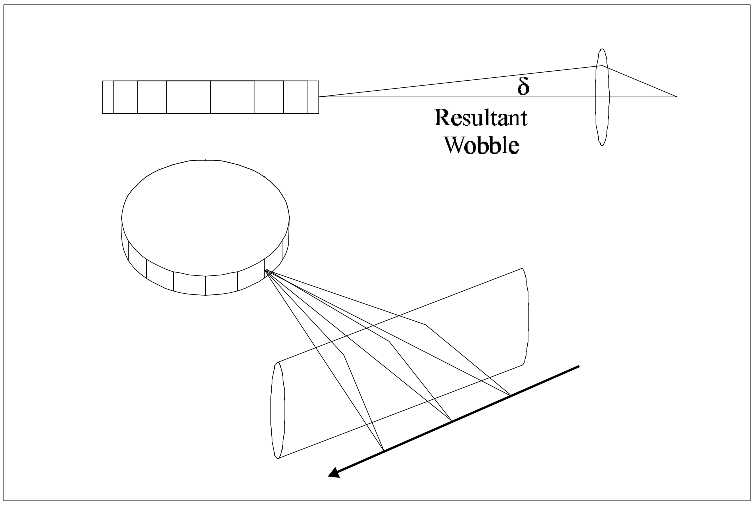

Figure 4 : Reducing Wobble

Although the first-order operation of this correction system is quite straightforward, actual systems must be carefully designed. While the majority of angular errors are to be found in the fabrication of the polygon, this system also corrects for bearing errors, etc. This is fortunate since fabrication errors are quite stable with time and the motor bearings will gradually wear. Since in general this wear tends to look for all practical purposes like facet errors, the system corrects these as well. Bearing quality can also be relaxed since arc-second polygons require are-second bearings to make use of the fabrication precision.

The polygonal scanner as mentioned earlier is basically a disk of material with optical flats on its periphery. When this optical element is rotated at high speed there are high stresses on the polygon material. Furthermore, the facets "paddle" the air and offer resistance to the driving motor.

These considerations need careful assessment in any high-speed printing system. Let us therefore consider the polygon requirements for a device printing an 11-in.-wide field and having a resolution of ~400 bits/in. and 400 scans/in. Furthermore, let us choose a photoreceptor velocity of 35 in./sec. The 35-in./sec photoreceptor velocity results in a printer capable of producing -4 pages/sec. The foregoing specifications are well in excess of any device on the market today and can serve as an excellent test case for polygon scanner technology. This hypothetical printer would consume data at a *minimum* rate of 62 x 10^6 bits/sec. Let us now look at the resultant parameters of the polygon required to achieve this imaging task.

For this discussion, assume a polygon diameter of 3.0 in, or 76.2 mm. This permits the polygon to have 24 facets of ~1.0 cm each. Since our photoreceptor velocity is 35 in./sec and the scan density is 400 lines/in., the polygon must produce 14000 scans/sec. With 24 facets the polygon rotational rate is ~583 revs/sec or 35,000 rpm. A book by Schlichting (1968) called "Boundary Layer Theory" provides the following data for drag on rotating disks. The Reynolds number R is given by the relation

$$R = \frac{r^2 w^2 r}{m}$$

where r is the disk or polygon radius, ω is the disk angular velocity, ρ is the air density, and μ the air viscosity. We shall also define a drag coefficient C_m which is related to the Reynolds number R by the relation,

$$C_m = \frac{3.87}{R^{1/2}}$$

which holds for a laminar flow region. The torque required to compensate for the resistance due to drag can be shown to be,

$$T = \frac{C_m r w^2 r^5}{2}$$

Finally, the power required to overcome "the windage" losses can be shown to be,

$$P = 1.877 \times 10^6 \; TZ \qquad \text{(Watts)}$$

where Z is the rpm and the torque T is in Nm. It should be noted that the coefficient C_m is dependent on many variables. If the polygon is enclosed in a tight enclosure for example, the constant changes from 3.87 to ~2.67. etc. Also, if turbulent flow is encountered the coefficient expression changes.

The generally accepted value for the Reynolds number R at which transition from laminar to turbulent flow occurs is 3×10^5. Also, the density of air ρ decreases with temperature and the kinematic viscosity μ increases. Substituting the appropriate values and constants, the Reynolds number is found to be 3.2×10^5, which is slightly above the laminar region. The torque T turns out to be $0.4\text{x}10^{-9}$ Nm for a "free" or unenclosed polygon. The power therefore works out to be,

$$P = (1.877\text{x}10^6)\ (0.4\text{x}10^{-9})\ (35{,}000) = 26\text{W}$$

It is interesting to note that a printer running at half-speed (17.5 in./ sec) with the other parameters the same as above requires an rpm of only 17,500. The Reynolds number turns out to be only 1.4×10^5. The resulting torque drops by about 80% and the power decreases even more dramatically to 2.7 W. Thus the effect of windage losses can be relatively high, depending on rotor diameter and rpm. This power loss is not, of course, just heat but can also result in significant "sirening." This noise must be damped out acoustically to prevent unwanted environmental disturbances. The more facets present on the disk periphery, the quieter the rotor since the apex joining the two facets does not project as far into the laminar or turbulent flow in the vicinity of the polygon surface. To some extent, the faceted nature of the polygon invalidates the disk approximation used earlier. The error introduced by the flat facets is in general not substantial, however.

The power losses discussed above are only for air-frictional effects. Motor bearings must also be considered as a source of friction. Whether one uses air bearings, grease bearings, or the more conventional ball bearings is a matter of tolerable service requirements, noise, and life.

The class of bearing or its precision will depend on how much the optical or electro-optic subsystem can tolerate facet “wobble”. Rotor unbalance is very crucial as well with regard to vibration and bearing life. The 3-in. polygon discussed above would generate almost 1.8kg of side load if the rotor had only 10^{-12}Nm. of unbalance. Fortunately, balancing can be cost-effectively performed to much tighter tolerances than the above.

We must now look at the rotational stresses that our polygon undergoes while spinning in excess of 580 revs/sec. The disk periphery is moving at 140ms^{-1} or ~ Mach 0.5.

Since our polygon must be mounted to the driving motor via its shaft, a centre bore in the polygon material must be provided. The polygon therefore becomes a spinning annulus. The stress on a spinning annulus (in Pa) can be shown to be,

$$S_t = (2.7\times10^{-3})\, wZ^2\left[(3+m)R_o^2 + (1-m)R_i^2\right]$$

where, *w* is the density of the rotor material in kgm^{-3}, Z is the rpm, R_o is the outer radius, R_i the inner radius (in m), and *m* is Poisson's ratio.

The above equation can be solved for the rpm Z, at which the stress S_t equals the yield stress of the material being used. This would result in a maximum value of Z for the rotor parameters used. Assuming that $R_o^2 >> R_i^2$ and making $m = 0.3$ (a good approximation), we can rewrite the equation as

$$Z_{max} = \left(\frac{110\times S_t}{wR_o^2}\right)^{1/2}$$

If we use the parameters for our 3-in (76mm) rotor, then we can generate a table comparing the performance of various materials. Such a comparison is shown in Table I. While mechanical finishing has a great deal to do with the ability of rotating mechanisms to take loads, we can make some general conclusions here. Copper and brass, although easy materials to work with mechanically, provide poor spinner materials. Glass and stainless steel (#51430) are roughly identical. A polygon to meet our requirements could be made out of crown glass and still have a safety factor of about 2. Type 7075 Aluminium has the greatest margin of safety from among the practical materials considered. Our 24-facet polygon could produce about 1.7×10^8 spots/sec at maximum Z. Beryllium is marginally the best material from a polygon performance standpoint, being able to generate over 3×10^8 spots/sec. This material, however, has a high toxicity when machined and is also expensive. Beryllium is therefore dropped from discussion due to its general complications and expense, and it is clearly not necessary unless rpm's in excess of 70,000 (2 x safety factor) are required. Actual surface profiles of the polygon mounting hole make a great deal of difference in the ultimate rpm capabilities of the device. Our concern in an actual product is not usually the maximum attainable performance, but rather cost/performance.

TABLE I : Selected Polygon Materials[a,b]

Material	Yield strength(MPa)	Density (kg/m^3)	Poisson ratio	Maximum rpm
Aluminium 7075-T6	503	2796	0.334	123,000
Stainless steel 51430	414	7750	0.300	67,000
Copper	117	8885	0.340	33,000
Brass	110	8359	0.340	33,000
Glass	138	2491	0.210	69,000
Beryllium	276	1827	0.250	110,000

[a] Outer radius, 1.43 in. (36mm)
[b] Inner radius, 0.25 in. (6.3mm)

The material that the polygon consists of should in general have a high strength-to-density ratio, low density, low Poisson's ratio, low thermal expansion coefficient, and be somewhat ductile and very stable. Depending on system requirements, there are several materials that can be used. Maximum performance and maximum cost are of course realised with exotic materials like beryllium. Various types of aluminium can be used to provide very good performance at acceptable prices.

As a last consideration for polygon scanners, we should concern out-selves with the rotation mechanism. Although one could drive the polygon from an air turbine, this might be unduly noisy. An electric motor is clearly best for the rpm regimes we are considering. There are many types of motors, of course, such as dc. induction, hysteresis-synchronous, etc. The system designer is left the task of selecting which motor technology best suits his needs. How the motor is driven, how the rpm is stabilised, etc., are all considerations that determine ultimate motor selection. The windage losses, bearing losses, and acceleration requirements will determine the ultimate power requirements of the polygon motor. Clearly the power requirements need not be very large for most practical systems, however.

In summary, the polygon deflector handles the laser-beam deflecting task very well. No particular aspect of either rotor or driver technology needs to be highly stressed to provide the required spots that our hypothetical 4-page/sec printer demands.

The Scanning Optics

There are two mains components to the scanning assembly : the scanner and the scan objective lens. At design time a choice must be made to use pre- or post-objective scanning, the two cases are shown in Figure 5. Each scheme has its own merits. Post-objective scanning is attractive since only a simple lens is needed (often only a single element lens). However, there is the disadvantage that the focal plane is curved, lying along a radius from the scanner axis. To achieve a flat focal plane pre-objective scanning is used. As can be seen from Figure 5, the lens design is much more complex, but the added complexity can bring additional benefits as well as flattening the focal plane; for example correction for any angular distortion one would get with the pre-objective scanning arrangement.

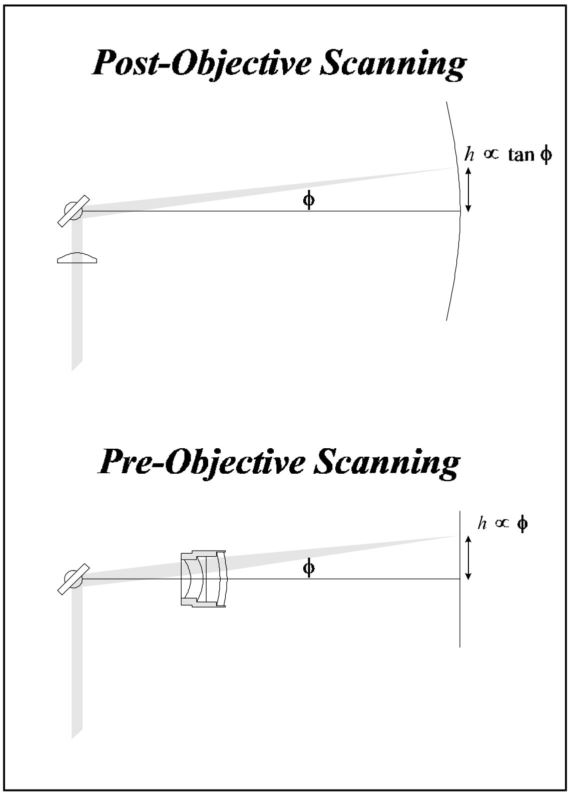

Figure 5 : Scanning Optics

The choice of scanning optics is determined to a large extent by the constraints of system resolution and overall size, both of which are dependent on the ***f number*** (written *f #*) of the lens used.

$$f\# = \frac{\text{Focal length}}{\text{Diameter}} = \frac{f}{D_1}$$

The resolution of the system will be determined by the spot size of the focused laser beam. As illustrated in Figure 6, this is dependent on the focal length of the lens, the diameter of the beam and the wavelength of the laser. The spot size at the beam waist is approximately given by :

$$d_0 = 1.64\, l\, (f\#)$$

This laser spot is considered to be "in focus" in a region on either side of the focal plane bounded by the ***depth of field***, Z_f.

$$Z_f = 4\, l\, (f\#)^2$$

If this depth of field is large enough, then a curved focal plane can be used since, as shown in Figure 6, the laser will remain sufficiently in focus across the entire scan. To make Z_f large we need to make the lens *f#* large. However, this results in the spot size being large too, which is undesirable for high resolution. Given the required resolution and the laser wavelength we can calculate back to find the necessary *f#* and hence the resultant Z_f.

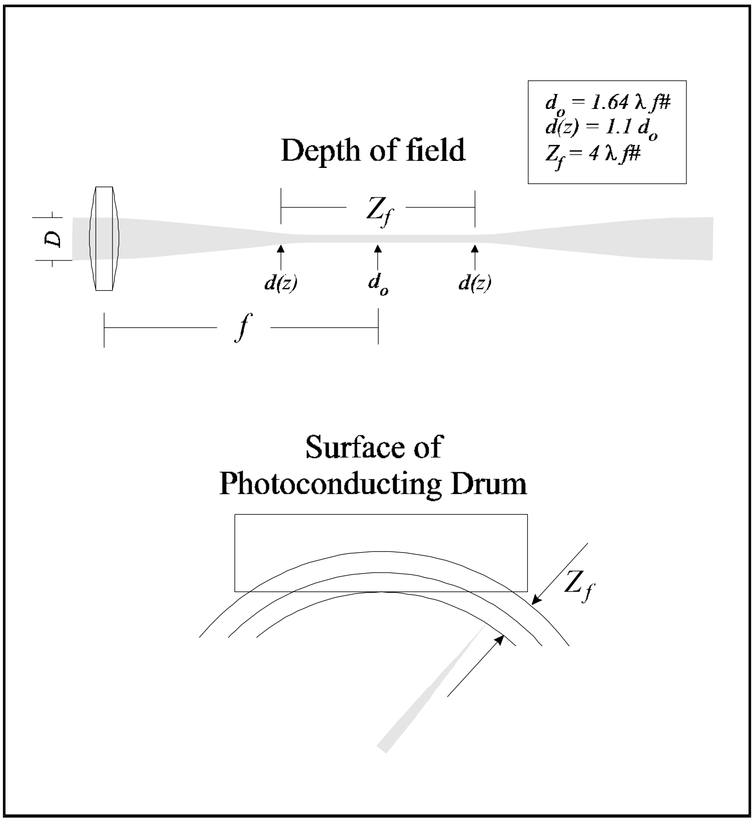

Figure 6: Depth of Field of Focused Spot

<u>*Example*</u>

Laser spot size, d_0 = 42µm
Laser wavelength λ = 632.8nm

Hence,

f# = d_0/(1.64 λ) = 42 µm / (1.64 x 0.6328 µm)
= 40

And so,

Depth of field Z_f = 4 x (0.6328µm) x $(40)^2$
= 4 mm.
