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Motors and Controllers (Drivers) for High-Performance Polygonal Scanners

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CONTENTS

5.1	Introduction.....	282
5.2	Polygonal Scanner Basics.....	282
5.2.1	Polygon Configurations	282
5.2.2	Polygon Rotation and Scan Angle Relationship.....	285
5.2.3	Polygon Speed Considerations.....	286
5.3	Case Study: A Film Recording System	288
5.3.1	System Performance Requirements	289
5.3.2	Spinner Parameters	290
5.3.3	Scanner Specification Tolerances	290
5.3.4	High-Performance, Defined	292
5.4	Motor Considerations.....	292
5.4.1	Motor Requirements.....	292
5.4.2	Hysteresis Synchronous Motor.....	294
5.4.3	Brushless DC Motor Characteristics	298
5.4.3.1	Torque and Winding Characteristics	299
5.4.3.2	Brushless Motor Circuit Model.....	299
5.4.3.3	Winding Configurations	302
5.4.3.4	Commutation Sensor Timing and Alignment.....	303
5.4.3.5	Rotor Configurations	303
5.5	Control System Design.....	306
5.5.1	AC Synchronous Motor Control.....	306
5.5.2	DC Brushless Motor Control	307
5.6	Application Examples	310
5.6.1	Military Vehicle Thermal Imager Scanner.....	310
5.6.2	Battery-Powered Thermal Imager Scanner	311
5.6.3	High-Speed Single-Faceted Scanner	313
5.6.4	Versatile Single Board Controller and Driver.....	314
5.7	Conclusions.....	317
	Acknowledgments	317
	References.....	318

5.1 INTRODUCTION

This chapter updates and expands upon the material covered by Gerald A. Rynkowski in *Optical Scanning*,¹ with greater emphasis being placed on brushless DC motors and the associated control electronics designed specifically for rotary scanning applications. Some background topics related to polygon scanning have been carried over to this chapter in order to clarify or illustrate control concepts. Other topics not directly related to motors and controllers, such as the discussion of air bearing design, have been omitted since these areas are covered in greater detail elsewhere in this book.

The availability of low-cost brushless DC motors and the continuing improvement in scanner control, as well as miniaturization of the drive electronics, have contributed greatly to the viability of optomechanical scanning in many new applications. Optomechanical scanning continues to be a cost-effective alternative to competing solid-state technologies. Several new application examples have been added that highlight the trend toward brushless DC motors and compact integrated control systems designed for military and commercial use.

Polygonal scanners have been designed, developed, and manufactured in all shapes and configurations during the past 35 years. These devices have been employed in military reconnaissance and earth resources studies, thermal imaging systems, film recorders, laser printers, flight simulators, and optical inspection systems, to name a few of the well-known applications. A common characteristic of all of these scanners is the requirement for precise control of polygon rotation, and consequently, the control of the beam scan. Recent advances in motor and control technologies have greatly improved the performance and efficiency of these scanners while simultaneously reducing the cost and size of the system.

This chapter explores the trends in motor and control technologies that are being utilized in today's polygonal scanners through the discussion of specific applications. In addition, motor characteristics, control techniques, and system models are presented to aid the optomechanical engineer in understanding these critical areas of scanning system design.

5.2 POLYGONAL SCANNER BASICS

Although a more thorough discussion of polygon geometry and scanning optics can be found elsewhere in this book, it will be useful to review some of the basic polygon configurations and optical designs as they influence the selection of the scan motor and control system. Also, a film recording system is presented in some detail in the next section in order to illustrate the influence of the scanner motor and controller characteristics on the overall system performance.

5.2.1 Polygon Configurations

In general, three types of scanner mirror configurations are popularly utilized in collimated or convergent, passive, or laser scanning optical systems. These rotating mirror spinners (polygons) are at the center of the electro-optical system. They direct incoming optical signals to a detector or steer outgoing modulated laser beams by virtue of their geometry and rotation about an axis.

The three most utilized scanner beam deflector configurations are the regular polygon, pyramidal, and the single-faceted cantilever design. The regular polygonal scanner is generally the most popular with system designers and can be utilized with either the collimated-beam or the convergent-beam scanning configurations. Figures 5.1 and 5.2 illustrate the two configurations using six-sided polygons having the spin axis projected into the page. In Figure 5.1 the facets are illuminated with a collimated beam and reflected to a concave mirror that focuses at a curved focal plane.

Figure 5.2 shows a lens system that focuses the collimated beam prior to being reflected at the scanner facets, and then converging at a focus. Comparing the two configurations, it is obvious that both focal image surfaces are curved. This presents a problem to the system designer, but is usually corrected optically with a suitable field-flattening correction lens system, or perhaps the recording surface is curved to conform to the focal surface.

FIGURE 5.1

Collimated beam scanning. (From Speedring Systems Group. "Ultra precise bearings for high speed use," 102-1; "Gas bearing design considerations," 102-2; "Rotating mirror scanners," 101-1, 101-2, 101-3. Technical Bulletins: Rochester Hills, MI. With permission.)

FIGURE 5.2

Convergent beam scanning. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

Another difference with regard to the polygon is that the convergent-beam bundle (Figure 5.2) uses less area of the facet than the collimated configuration. However, maximum utilization of the facet area is desirable because the facet surface flatness irregularities tend to be averaged out, and therefore, minimize modulation of the exiting-beam scanning angles. Most precision polygonal scanning systems use the collimated beam scanning configuration, which utilizes a larger proportion of the area of the facets.

Figure 5.3 illustrates a pyramidal mirror scanner commonly used with the rotational and optical axes parallel, but not coincident. Note that either the collimated or convergent configuration can be utilized with this design.

Figure 5.4 illustrates a regular polygonal scanner in which the optical axis is normal to the rotational axis, or where the angle is acute to normal. Note that when the two axes, optical and rotational, are normal, the beam can reflect back upon itself.

Shown in Figure 5.5 is a single-faceted cantilevered scanner with the beam and rotational axes coincident and reflecting from a 45° facet, and thereby generating a continuous 360° scan angle and a circular focused scan line.

This configuration has been used in passive infrared scanning systems having long focal length and requiring a large aperture. Nine-inch, clear-aperture scanners have been manufactured in this configuration for high collection efficiency.

This type of beam deflector design is also popular in scanning systems that are used in the image setting machines sold to the printing market. Many of these image setting machines have an "internal drum" design which involves the placement of a large piece of film on the inside surface of a cylinder. The single-faceted "monogon" beam deflector rotates at high speed and scans a laser spot across the width of the film as it travels the length of the drum. Figure 5.6 illustrates a monogon beam deflector designed for rotational speeds exceeding 30,000 rpm.

FIGURE 5.3

Parallel, but not coincident, optical and rotational axes. (From Speedring Systems Group. "Ultra precise bearings for high speed use," 102-1; "Gas bearing design considerations," 102-2; "Rotating mirror scanners," 101-1, 101-2, 101-3. Technical Bulletins: Rochester Hills, MI. With permission.)

FIGURE 5.4

Optical and rotational axes normal. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

FIGURE 5.5

Parallel and coincident optical and rotational axis. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

5.2.2 Polygon Rotation and Scan Angle Relationship

At this point, it is noteworthy to realize the relation between the facet angle and scan angle. The facet angle is defined as $360^\circ/N$ (N = number of facets). The optical scan angle may be expressed as:

$$\text{Scan angle (degrees)} = \frac{720}{N}$$

for $N \geq 2$. Observe that for $N \geq 2$, the optical scan angle is two times the shaft angle. This angle-doubling effect must obviously be considered when relating the shaft and facet parameters and their effects on the angular position of the focused spot at the focal plane.

FIGURE 5.6
Monogon beam deflector.

The optical angle-doubling effect places an even greater demand on the control of the polygon rotational velocity and must be carefully considered if the desired system accuracy is to be achieved.

The scanner rotational speed may be expressed as:

$$\text{rpm} = \frac{60W}{N}$$

where W = line scans/s, and N = number of facets.

An increase in the number of facets reduces the motor speed requirements as well as the maximum scan angle. However, the usable scan angle may in some cases also be limited by aperture size and the allowable vignette effect. In practice, the optical design will usually dictate the number of facets and consequently the motor and controller will have to be selected to accommodate the optical system designer. Figure 5.7 illustrates a small 12-faceted polygon mirror.

5.2.3 Polygon Speed Considerations

When a range of polygon rotation speeds are allowed by the optical design, it is best to avoid configurations that require speeds that are very low or very high. Problems with motor controllability may occur at speeds below about 60 rpm and motor efficiency may suffer when speeds exceeding 60,000 rpm are specified. To achieve good speed regulation at very low polygon rotation speeds, special motor and control designs are often required that will lead to increased system cost. A polygon rotating at 60 rpm and specified for 10 ppm (10 parts per million, or 0.001%) speed regulation will likely require a sinusoidally driven slotless brushless DC motor and complex controller design to achieve this level of performance.

Another complication associated with low-speed designs involves the selection of the velocity feedback device. Often the feedback device will be an optical encoder (Figure 5.8),

FIGURE 5.7
Twelve-faceted polygon.

FIGURE 5.8
Optical encoder, disc, and readout electronics.

which functions both as a tachometer to monitor the polygon speed, and in some systems, as a position sensor for reporting the true position of the polygon to the scan processing electronics. Today's high-performance speed control systems operate using phase-lock loop techniques that provide excellent short-term as well as long-term speed regulation. These systems operate by comparing the frequency and phase of a stable reference signal with that of the polygon encoder, thereby generating an error signal, which is used to adjust the polygon speed. In order to achieve good speed control at low speeds, a high-resolution/high-accuracy encoder is necessary.

Depending on the polygon inertia, bearing friction, and the level of disturbances present, an encoder line density greater than 10,000 lines (counts) per revolution may be required for a 60 rpm scanner. Optical encoders having greater than a few thousand line counts per

revolution will also contribute to increased system cost since the disc pattern and the edge detection functions must be more precise.

As the polygon operating speed increases, fewer pulses per revolution from the encoder are required to achieve the same level of performance, all other factors being equal. This is due to the fact that at higher speeds, lower encoder resolutions can still produce an adequate number of pulses or "speed updates" per second from the encoder and allow for a reasonably fast control loop bandwidth. Higher control system bandwidth is desirable because the control loop can more readily react to short duration disturbances in speed, which may not be adequately attenuated by the polygon inertia.

The control system will receive some average polygon speed between encoder pulses from the phase detector, but it is essentially operating open loop until the next pulse arrives and updates the speed based on the encoder pulse phase relative to the reference clock. During this period between speed updates the polygon speed will generally decrease from the set point (and the last update) until the next encoder pulse arrives and the control system makes a correction. Therefore to achieve a specified update rate or bandwidth for the control system, the slower polygon will require a higher resolution encoder with correspondingly better pattern accuracy.

The actual speed change between encoder updates is a function of many factors, including the operating speed, total rotating inertia of the scanner, the amplitude and frequency of disturbances, the control system gain, and the friction. In general, higher polygon/motor inertia and lower bearing and windage friction are beneficial and will reduce the short-term speed variations present in the scanner. This will be discussed in greater detail in Sec. 5, which deals with the control system design.

At the other extreme, high operating speeds require that the polygon and the entire rotating assembly exhibit exceptionally low imbalance, ideally less than 10 $\mu\text{in-oz}$. Often this requires that the scanner must be balanced in two planes: at the polygon and at the motor/encoder location. This is necessary not only for maintaining the mechanical integrity and life of the rotating components, but also for achieving precise speed control within one revolution of the scanner. Any imbalance that causes concentricity error at the encoder will result in a sinusoidal scanner speed variation. This is especially true for air bearing scanners where the bearing stiffness is lower and allows for larger concentricity errors to be produced.

Also, the motor efficiency is adversely affected at high speeds, especially when the commutation frequency exceeds 1000 cycles/s. Special motor designs are required for efficient high-speed operation and these designs usually require expensive development time and have higher unit cost.

5.3 CASE STUDY: A FILM RECORDING SYSTEM

A film recording scanning system has been selected as a reference subsystem for purposes of discussing the scanner parameters as well as the dynamic performance requirements involving the motor and control system design. Figure 5.9 depicts a laser recording system capable of recording high-resolution video or digital data on film. The rotating polygon (spinner) generates a line scan at the film plane using a focused, intensity-modulated laser beam. The laser exposes the film in proportion to the intensity modulation in the video or digital signal. Line-to-line scan is accomplished by moving the photographic

FIGURE 5.9

Film recording system. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

film at constant velocity and recording a continuous corridor of data limited only by the length of film. The film controller provides precise control of film velocity, which is locked to the polygon rotation. The expanded and collimated laser beam is intensity modulated with video or digital data and then scanned by the facets of the spinner to the film plane. A field correction lens ($F-\theta$) is used to focus the beam, to linearize the scan line with respect to the scan angle, and thereby provide a uniform spot size along the line at the film plane.

The scanner assembly contains a 12-faceted polygon required to perform the optical scan function. The rotating mirror, its drive motor rotor, and a precision optical tachometer are supported by externally pressurized gas bearings. The electronic controller provides precise motor speed control and synchronization between the reference frequency sync generator and the high-density data track of the optical encoder. The encoder also supplies an index pulse used for facet identification and derivation of the synchronized field frequency that is required for some raster scanning systems, as well as pixel registration and control of the film drive motor.

5.3.1 System Performance Requirements

The system performance parameters for our example digital film recorder are discussed in the following paragraphs. These parameters are summarized in Table 5.1 and are typical and representative of a recently manufactured film recording system.

The system resolution requirements are defined at the film plane since all optical, scanning, and film transport errors will become evident on the recording media. The application requires 10,000 pixels of digital data per line at the scan plane using a 10- μm

TABLE 5.1**Film Recorder System Requirements**

Line resolution (both directions)	10,000 pixels/line
Line scan length	13.97 cm
Scan rate	1200 lines/s
Film speed	1.6764 cm/s
Pixel frequency (clock)	12 MHz
Pixel diameter	10 μm at $1/e^2$
Pixel-to-pixel spacing	13.97 μm

Source: Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991.

spot diameter measured at the $1/e^2$ irradiance level. One can calculate that for a 13.97-cm line scan length the pixel spacing, center to center, must be 13.97 μm , as must the spacing between scan lines. The line spacing variance, or film transport jitter, is conservatively specified to be less than ± 5 ppm (half the nominal spot size). For a reasonable throughput, the application dictates a scan rate requirement of 1200 lines/s. From this information the calculated pixel frequency is found to be 12 MHz (1200 lines/s $\times$ 10,000 pixels/line), and the film speed needed is 1.6764 cm/s (1200 lines/s $\times$ 13.97 μm /line).

5.3.2 Spinner Parameters

The polygon specification is determined and driven by the form, fit, and functional performances set by the optical requirements of the system. At this point, the optical engineer must optimize the design of the optical elements, which includes specifying the polygon type, facet number, facet width and height, inscribed diameter of the polygon, facet flatness and reflectance, and rotating speed. Owing to the interactions of the specifications and the high-accuracy requirements, the spinner is addressed as a scanner subsystem to allow the scanner designer to make trade-off decisions within the limits imposed by the optical and system performance requirements.

The scanner subsystem in our film recorder example consists of a one-piece beryllium scan mirror and shaft, suspended on hydrostatic gas bearings, and driven by a servo-controlled AC synchronous motor. The $F-\theta$ lens is designed to function with a 60° optical scan entrance angle which dictates a 30° facet angle specification for the polygon. The number of facets is therefore calculated to be 12, and a motor speed of 100 rev/s, or 6000 rpm, generates 1200 scan lines per second. Depicted in Table 5.2 is a summary of the scanner polygon requirements.

5.3.3 Scanner Specification Tolerances

Scanner specification tolerances are determined by the permissible static and dynamic pixel position errors acceptable at the film plane. These worst-case errors are referenced back through the optical system and scanner subsystem to be distributed and budgeted between the operational elements and reference datum. The acceptable variances are often specified as a percentage of pixel-to-pixel angle, pixel diameter, pixel-to-pixel spacing, or the motor speed regulation (stability) over one or more revolutions. The conversion of these variances to meaningful and quantifiable units is necessary for manufacturing, measurement, inspection, and testing of the scanning system components.

TABLE 5.2
Film Recorder Polygon Requirements

Number of facets	12
Facet angle	30°
Inscribed diameter	4.0 in
Facet height	0.5 in
Facet reflectance	89%–95%
Facet flatness	$\lambda/20$
Facet quality	MIL-F-48616
Scan rate	1200 scans/s
Rotational speed	6000 rpm

Source: Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991.

TABLE 5.3
Film Recorder Scanner Characteristics and Tolerances

Characteristic	Tolerance	Comments
<i>Polygon data</i>		
Number of facets	N.A.	Determined by scan angle
Facet angle	± 10 arc sec	One pixel-pixel angle
Diameter	N.A.	Controlled by facet width dimension
Facet width	1.035 in mm	0.020-in roll-off
Facet height	0.5 in mm	0.020-in roll-off
Flatness	$\lambda/20$ max	Spot control
Reflectance	$\pm 3\%$	Tolerance
Apex angle	1.00 arc s	Total variation—10% of line–line angle
<i>Speed regulation</i>		
1 revolution	± 10 ppm	± 1.08 arc s/line
Long term	± 50 ppm	± 5.40 arc s/line

Note: Scan error for any 12 scans $\leq \pm 12.96$ arc s. N.A., not applicable.

Source: Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991.

Our primary concern here is to relate the scanning system specifications, which ultimately determine the quality of the scanned image, to the performance requirements that are imposed on the motor and control system. It is apparent (Table 5.3) that the polygon rotation regulation plays a major role in the scanning system performance and that the design of the motor and control system must be given careful consideration in order to achieve the precise pixel placement accuracy.

Precision closed-loop control of the motor speed is essential if the performance targets outlined in Table 5.1 are to be met. To achieve the level of speed regulation required by the 13.97- μm pixel spacing specification, a phase-lock loop control system with a quartz oscillator frequency reference will be required. The 13.97- μm pixel spacing translates to a polygon speed regulation requirement of 0.001% (10 ppm) within one rotation of the scanner and over the time required to write the full page of the image onto the film. Speed

TABLE 5.4

Scanner Performance Comparison

Characteristics	Reference system	State-of-art system
Facet number	12	20
Facet tolerance	± 10 arc s	± 1 arc s
Apex angle error	± 0.4 arc s	± 0.2 arc s
Speed	6000 rpm	28,800 rpm
Scan rate	1200 scans/s	9600 scans/s
Speed regulation/rev	<10 ppm	<1 ppm
Pixels/scan	10,000	50,000
Pixel/jitter/rev	< ± 25 ns	< ± 2 ns
Pixel clock	12 MHz	480 MHz

Source: Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991.

variations within one turn of the polygon will produce an uneven scan line length, which will be visible as a variation along the edge of the film opposite the start of scan. Slower speed variations that occur over many revolutions but still within the same film frame may produce other undesirable image artifacts and distortions.

Subtle variations in the printed image such as shading and banding can also result from short-term speed changes within the scanner, which may occur over a few revolutions, and the human eye has a remarkable ability to detect these otherwise minor variations within the image.

5.3.4 High-Performance, Defined

Table 5.4 depicts the performance of the film recorder reference system in comparison to a state-of-the-art recording system considered by many as the highest resolution and fastest system manufactured to date. Note that the polygon speed regulation required in the state-of-the-art system is less than one part per million, or 0.0001%.

5.4 MOTOR CONSIDERATIONS

5.4.1 Motor Requirements

In the most demanding scanning applications, which require high speed and exceptional accuracy, the precision of the integral polygon, shaft, and bearing assembly must not be degraded by the introduction of the motor rotor. This places a heavy burden on motor rotor selection.

Any motor rotor attached to the shaft must have very stable and predictable characteristics with regard to strength and temperature, and if possible, the rotor material should be homogeneous. If the rotor is of a complex mechanical configuration and consists of laminations and windings, the assembly may not maintain a precision balance (less than 20 μ in-oz) when operating at high speeds. Additionally, thermal expansion and high

centrifugal forces may shift and reposition the rotor and perhaps cause a catastrophic failure in an air bearing scanner.

Two motor designs are considered for use with high- and low-speed air bearing and ball bearing scanners, respectively; they are the hysteresis synchronous and the DC brushless. Pictured in Figure 5.10 is a high-speed DC brushless motor with integral Hall effect sensors for commutation and the associated rotor magnet mounted on a brass encoder hub assembly. Figure 5.11 depicts the two main components of a hysteresis synchronous motor: the stator and the hysteresis ring rotor.

FIGURE 5.10
Brushless DC motor: stator and rotor.

FIGURE 5.11
Hysteresis synchronous motor: stator and rotor. (From "Rotors, H.C. "The hysteresis motor—advances which permit economical fractional horsepower ratings," AIEE Technical Paper 47-218, 1947. With permission.)

5.4.2 Hysteresis Synchronous Motor

The difficult rotor mechanical stability requirements for high-speed scanner operation are easily achieved with the use of a hysteresis synchronous motor (Figure 5.11). The hysteresis rotor is uncommonly simple in design and consists of a cylinder of hardened cobalt steel that is heat shrunk onto the rotor shaft assembly. Careful calculations are required with regard to the centrifugal forces and thermal expansion influences on the rotor and shaft for safe and reliable operation. This type of motor is well suited for operation at speeds ranging from 1000 rpm to 120,000 rpm. Motors having output power as large as 2.2 kw have been successfully used on large-aperture IR scanning systems operating at 6000 rpm.

The operation of a hysteresis synchronous motor relies on the magnetic hysteresis characteristics of the rotor material. As the magnetizing force from a suitably powered stator (not unlike that used with reluctance-type motors) is applied to a cobalt steel rotor ring or cylinder, the induced rotor magnetic flux density will follow the stator coil current, as illustrated in Figure 5.12.

The sinusoidal current is shown to increase from zero, along the initial magnetization curve, to point (a), thereby magnetizing the material to a corresponding flux level at the peak of the sinusoid. As the current decreases to zero, the rotor remains magnetized at point (b). If the current at this point in time were to remain at zero, the rotor would be permanently magnetized at the point (b) flux level. However, as the current reverses direction, the flux reduces to zero at some negative value of current as shown at point (c). Further decreases in current (negative direction) reverse the direction of flux as shown at

FIGURE 5.12

Magnetic hysteresis curve. (From Lloyd, T.C. *Electric Motors and Their Applications*; Wiley: New York, 1969. With permission.)

point (d), corresponding with the negative peak of the current. The process continues to point (e) and back to point (a), completing the loop for one cycle of current. The figure generated is called a magnetic hysteresis loop. In physics, hysteresis is defined as a lag in the magnetization behind a varying magnetizing force.

By analogy, as the axis of the magnetizing force rotates, the axis of the lagging force of the rotor will accelerate the rotor in the same direction as the rotating field. As the rotor accelerates, its speed will increase until it reaches the synchronous rotating frequency of the field. At this point, the rotor becomes permanently magnetized and follows the rotating field in synchronism.

The synchronous speed of the rotor can be calculated with the following expression:

$$\text{rpm} = \frac{120f}{N}$$

where f = line frequency (Hz) and N = number of poles.

Figure 5.13 depicts a typical speed versus torque characteristic curve for a hysteresis synchronous motor.

If a fixed line voltage and frequency is applied to the stator winding of the motor, an accelerating torque is developed equal to the starting torque, T_s , shown at point A. As the speed of the rotor increases, the operating point on the curve moves through the maximum torque developed at point B, and continues through point C, at which time synchronous speed is reached. The final operating point, D, is determined by the operating load torque presented to the shaft at torque level T_0 . Note that if the operating load torque is greater than the in-sync torque, synchronous speed will not be reached.

Figure 5.14 is a vector representation of the rotating magnetizing field and the magnetized rotor field while in synchronism. Note that the rotor field vector lags the magnetizing field by an angle α . The operating torque (as developed by the motor in synchronism) is in proportion to the sine of the angle α in electrical degrees. If the load torque and stator frequency are absolutely constant, their frequencies will be precisely equal.

However, should the torque angle be modulated sinusoidally, as indicated in Figure 5.14 (with a torque variance of $\pm\beta$), the rotor vector will advance and retard as indicated about the average angle α . The long-term average speed will be as constant as the applied stator source frequency, but the instantaneous speed will follow the derivative of the sine wave

FIGURE 5.13

Speed/torque performance curve. (From Lloyd, T.C. *Electric Motors and Their Applications*; Wiley: New York, 1969. With permission.)

FIGURE 5.14

Stator/rotor field vectors. (From Lloyd, T.C. *Electric Motors and Their Applications*; Wiley: New York, 1969. With permission.)

on a one-to-one basis. The effect of torque perturbations that are not attenuated by system inertia will also modulate the shaft speed accordingly.

A characteristic of hysteresis synchronous motors (and other second-order devices and systems) called “hunting” may be observed when operating the motor in a system having low losses and damping factor. The motor rotor will oscillate in a sine wave fashion, not unlike that depicted in Figure 5.14, if perturbed by applied forces internal or external to the system. If the perturbations are sustained, the oscillations will also be sustained.

However, if the perturbations are not sustained, the oscillations will diminish in amplitude to essentially zero. The internal damping factor of the motor can be influenced by the rotor resistivity, rotor-to-stator coupling coefficient, and driver source and stator impedance. In a typical open-loop operation (no external velocity or position feedback) the oscillations may not be predictable and, therefore, may suddenly appear due to an unknown source or sources of perturbing forces. The amplitude of the oscillations in shaft degrees can typically range from 1° to 10°, and, as a practical matter, is very difficult to calculate; however, the rotor oscillating (hunting) frequency (W_n) can be estimated as

$$W_n = \sqrt{\frac{K}{I}}$$

where W_n = natural resonant frequency (rad/s), K = motor stiffness (in-oz/rad, or $\Delta T/\Delta a$), and I = shaft moment of inertia (in-oz s²).

The maximum instantaneous speed is determined by setting the derivative of the sine function to zero, and then calculating the maximum positional rate of change in radians per second:

$$\text{Change in speed (rad/s)} = \pm A_p W_n$$

where $A_p = \pm b$ rekey and W_n = natural resonant frequency (rad/s).

FIGURE 5.15

Velocity regulation versus speed. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

The maximum change in speed is often expressed as a percentage change relative to the nominal operating speed of the motor:

$$\text{Velocity regulation (\%)} = 100 \left(\frac{A_p W_n}{W_s} \right)$$

where W_s = nominal operating speed (rad/s).

Figure 5.15 shows two curves of percent velocity regulation versus speed in rpm, for a typical open-loop scanning system having peak angular displacements of 1° and 5° . A four-pole motor with a peak torque of 10 oz-in and having a total inertia of 0.076 oz-in s^2 was used for the calculations in Figure 5.15. Note that for peak angular displacements of 1° , velocity regulation of 0.05% could be claimed for all speeds greater than 3000 rpm. However, should the peak angular displacements increase to 5° , then 0.05% velocity regulation is only obtainable at speeds greater than 14,000 rpm. Figure 5.15 illustrates that, for a typical open-loop scanning system operating at speeds above 3000 rpm, the system designer can expect variance in velocity ranging from less than 0.05% to as high as 0.25%. In conclusion, if system speed regulation requirements must be guaranteed to be less than 0.05% (500 ppm), closed-loop control of the motor speed using phase position feedback must be incorporated.

Another advantage of hysteresis synchronous motors in precision scanners is the near absence of rotor eddy currents when the rotor is synchronized with the rotating stator field. These currents can produce increased I^2R rotor losses that can cause rotor/shaft distortions due to generated temperature gradients and produce adverse effects, especially in air bearing designs. The primary source of rotor eddy current losses is from the spurious flux changes that occur as the rotor passes the stator slots. These parasitic losses are often referred to as "slot effect losses" and can be very significant at high

speeds, rendering the device very inefficient as is often noted in older designs. Careful stator design can minimize these losses to the extent that the primary source of rotor/shaft heating is through the air bearing gap from the stator or due to air friction. Any residual heat generated by stator losses may be further reduced and diverted away from the bearing/rotor system by water or air cooling of the stator housing to minimize the rotor/shaft temperature rise.

In summary, AC hysteresis-synchronous motors were a natural choice in early polygon scanners, especially for high-speed applications. Simplicity of construction and reliable, maintenance-free operation were key advantages. Also, since the long-term shaft speed was precisely determined by the excitation frequency, no speed control system was required in order to produce acceptable results in low-cost systems. However, as scanner speed control requirements became more critical, feedback devices such as optical encoders were added in order to control the short-term speed variation or "hunting" found in this type of motor. This required increase in control complexity paved the way for the entry of DC brushless motors for precision scanning applications.

5.4.3 Brushless DC Motor Characteristics

The brushless DC motor (Figure 5.10) is well suited for speeds ranging from near zero to as high as 80,000 rpm. These motors exhibit the same characteristic as brush commutated types and can therefore be used in the same applications. They are also suited for velocity and position servo applications since they have a near ideal, linear control characteristic, meaning that the torque produced by the motor is in direct proportion to the applied current.

The elimination of brushes and commutating bars provides reduced electromagnetic interference, higher operating speeds and reliability, with no brush material debris from brush wear. The commutating switching function is accomplished by using magnetic or optical rotor position sensors that control the electronic commutating logic switching sequence. In actual operation, a DC current is applied to the stator windings, which generates a magnetic field that attracts the permanent magnets of the rotor, causing rotation. As the rotor magnetic field aligns with the stator field, the field currents are switched, thereby rotating the stator field and the rotor magnets follow accordingly.

The rotor will continue to accelerate until the motor output torque is equal to the load torque. Under no load conditions, the motor speed will increase until the back electromotive force (BEMF) generates a voltage equal to the stator supply voltage minus the DC winding resistance voltage drop. At this point, the rotor speed reaches an equilibrium level as determined by the BEMF motor constant.

The open-loop speed stability and regulation under controlled power supply and temperature conditions is usually 1%–5%, so the device is typically used with closed-loop feedback control. In the closed-loop mode of operation, particularly in the phase-lock loop configuration, short-term speed stability of 1 ppm is obtainable. However, on a long-term basis, the speed stability and accuracy are only as good as the reference source, which is routinely specified at 50 ppm or less for quartz crystal oscillator references, which are used in phase-lock loop speed control systems.

The brushless DC motor, when properly commutated, will exhibit the same performance characteristics as a brush commutated DC motor, and for servo analysis the two may be considered equivalent devices. Both motor types may be characterized by the same set of parameters as described in the following discussion.

5.4.3.1 Torque and Winding Characteristics

The basic torque waveform of a brushless DC motor has a sinusoidal or trapezoidal shape. It is the result of the interaction between the rotor and stator magnetic fields, and is defined as the output torque generated relative to rotor position when a constant DC current is applied between two motor leads. With constant current drive, the torque waveform follows the shape of the BEMF voltage waveform generated at any two motor winding leads. The frequency of the BEMF voltage waveform is equal to the number of pole pairs in the motor times the speed in revolutions per second. The BEMF waveform is easily observed by rotating the motor at a constant speed and is in fact often used to characterize the motor during testing.

The brushless DC motor exhibits torque/speed characteristics similar to a conventional brush-type DC motor. The stator excitation currents may be square wave or sinusoidal and should be applied in a sequence that provides a constant output torque with shaft rotation. Square wave excitation results in a small ripple in the output torque due to the finite commutation angle.

The commutation angle is defined as the angle the rotor must rotate through before the windings are switched. Ripple torque is typically expressed as a percentage of average-to-peak torque ratio and is present whenever the windings are switched by a step function either electrically via solid-state switches or mechanically via brushes. In brushless DC motors designed for square wave excitation, the ripple torque can be minimized by reducing the commutation angle through the use of a larger number of phases, which also improves motor efficiency. For a two-phase brushless motor, the commutation angle is 90 electrical degrees, which yields the largest ripple torque of about 17% average-to-peak. A three-phase delta-wound motor is shown in Figure 5.16. The commutation angle is 60° and the ripple torque is approximately 7% average-to-peak. Since two-thirds of the available windings are used at any one time, compared to one-half for the two-phase motor, the three-phase system is more efficient.

The torque waveforms shown in Figure 5.16 have a sinusoidal shape. For square wave excitation of the motor a trapezoidal torque waveform will produce improved torque uniformity. A trapezoidal torque waveform can be obtained by using a salient pole structure in conjunction with the necessary lamination/winding configuration. In practice, the trapezoidal torque waveform does not have a perfectly flat top and the benefit to torque ripple reduction may be small.

The commutation points and output torque for a three-phase brushless motor are shown in Figure 5.16. Each phase (winding) is energized in the proper sequence and polarity to produce the sum torque shown at the bottom of Figure 5.16 and is calculated to be equivalent to the current times the torque sensitivity of the motor (IK_T).

5.4.3.2 Brushless Motor Circuit Model

The equivalent electrical circuit model for a DC brushless motor is shown in Figure 5.17. This model can be used to develop the electrical and speed–torque characteristic equations, which are used to predict the motor performance in a specific application.

The electrical equation is

$$V_T = IR + L di / dt + K_B \omega \quad (5.1)$$

where V_T = the terminal voltage across the active commutated phase, I = sum of the phase currents into the motor, R = equivalent input resistance of the active commutated phase,

FIGURE 5.16

Three-phase motor torque and commutation points. (From Axsys Technologies Motion Control Products Division, San Diego, CA, *Brushless Motor Sourcebook*; Axsys: San Diego, CA, 1998. With permission.)

FIGURE 5.17

DC brushless motor equivalent circuit. (From Axsys Technologies Motion Control Products Division, San Diego, CA, *Brushless Motor Sourcebook*; Axsys: San Diego, CA, 1998. With permission.)

L = equivalent input inductance of the active commutate phase, K_B = BEMF constant of the active commutated phase, and ω = angular velocity of the rotor.

If the electrical time constant of the brushless DC motor is substantially less than the period of commutation, the steady-state equation describing the voltage across the motor may be written as:

$$V_T = IR + K_B \omega \quad (5.2)$$

The torque developed by the brushless DC motor is proportional to the input current such that:

$$T = IK_T$$

where K_T = the torque sensitivity (oz-in/A).

Solving for I and substituting into Equation 5.2 yields:

$$V_T = T/K_T R + K_B \omega \quad (5.3)$$

The first term represents the voltage required to produce the desired torque, and the second term represents the voltage required to overcome the BEMF of the winding at the desired operating speed. If we solve Equation 5.3 for rotor speed we obtain:

$$\omega = \left(\frac{V_T}{K_B} \right) - \left(\frac{TR}{K_B K_T} \right) \quad (5.4)$$

Equation 5.4 is the speed–torque relationship for a permanent magnet DC motor. A family of speed–torque curves represented by Equation 5.4 is shown in Figure 5.18. The no-load speed may be obtained by substituting $T = 0$ into Equation 5.4:

$$\omega(\text{no load}) = \frac{V_T}{K_B}$$

Stall torque can be found by substituting $\omega = 0$ into Equation 5.4:

$$T(\text{stall}) = \frac{K_T V_T}{R} = IK_T$$

The slopes of the parallel line speed curves of Figure 5.18 may be expressed by:

$$\frac{R}{K_B K_T} = \omega(\text{no load})/T(\text{stall})$$

FIGURE 5.18

DC motor characteristic curves. (From Axsys Technologies Motion Control Products Division, San Diego, CA, *Brushless Motor Sourcebook*; Axsys: San Diego, CA, 1998. With permission.)

Since the speed–torque curves are linear, their construction is not required for predicting motor performance. The system designer can calculate the required information for servo performance from the basic motor parameters given by the manufacturer.

5.4.3.3 Winding Configurations

Almost all of the brushless motors and drives produced today will be of the three-phase configuration, although two-phase motors have unique advantages, which are exploited in very low-speed applications. Three-phase windings can be connected in either a “delta” or “Y” configuration as shown in Figure 5.19.

Excitation currents into the windings can be switched full on, full off, or be applied as a sinusoidal function depending on the application. The switch mode drive is the most commonly used system because it results in the most efficient use of the electronics. Two switches per phase (winding) terminal are required for the switch mode drive system. Therefore, only six switches are required for either the “Y” or “delta” configuration.

The delta windings form a continuous loop, so current flows through all three windings regardless of which pair of terminals are connected to the power supply. Since the internal resistance of each phase is equal, the current divides unequally, with two-thirds flowing through the one winding connected directly between the switched terminals, and one-third flowing through the two series-connected windings appearing in parallel with it. This results in switching only one-third of the total current from one winding to another as the windings are commutated.

For the “Y” connection, current flows through the two windings between the switched terminals. The third winding is isolated and carries no current. As the windings are commutated, the full load current must be switched from terminal to terminal. Owing to the electrical time constant of the windings, it takes a finite amount of time for the current to reach full value. At high motor speeds, the electrical time constant ($T_E = L/R$) may limit the switched current from reaching full load value during the commutation interval, and thus limits the generated torque. This is one of the reasons the delta configuration is preferred for applications requiring high operating speed. Other considerations are manufacturing factors, which permit the delta configuration to be fabricated with lower BEMF constant, resistance, and inductance. A lower BEMF constant allows the use of more common low-voltage power supplies, and the solid-state switches will not be required to switch high voltage. For other than high-speed applications, the “Y” connection is preferred because

FIGURE 5.19
Three-phase motor winding configurations.

it provides greater motor efficiency when used in conjunction with brushless motors designed to generate a trapezoidal torque waveform.

5.4.3.4 Commutation Sensor Timing and Alignment

A brushless DC motor duplicates the performance characteristics of a DC motor only when its windings are properly commutated, which means that the winding currents are applied at the proper time, polarity, and in the correct order. Proper commutation involves the timing and sequence of stator winding excitation. Winding excitation must be timed to coincide with the rotor position that will produce optimum torque. The excitation sequence controls the polarity of generated torque, and therefore the direction of rotation. Rotor position sensors provide the information necessary for proper commutation. Sensor outputs are decoded by the commutation logic electronics and are fed to the power drive circuit, and activate the solid-state switches that control the winding current.

A useful method to achieve correct commutation timing is to align the position sensor to the BEMF waveform. Since the BEMF waveform is qualitatively equivalent to the torque waveform, the test motor can be driven at a constant speed by another motor, and the position sensors aligned to the generated BEMF waveform. The sensor transition points relative to the corresponding BEMF waveforms should be coincident when correct commutation has been achieved. For critical applications that require the commutation points to be optimized, the motor should be operated at its rated load point, and then the position sensors should be adjusted until the average winding current is at its minimum value.

The commutation points and output torque for a three-phase brushless motor are shown in Figure 5.16. The commutation angle is 60 electrical degrees. The windings are switched "on" at 30 electrical degrees before the peak torque position, and switched "off" at 30 electrical degrees after the peak torque position. The current polarity must be reversed for negative torque peaks to produce continuous rotation. To identify each of the six commutation points, a minimum of three logic signals are required, as shown in Figure 5.20. The logic signals are generated by three sensors which are spaced 60 electrical degrees apart and produce a 50% duty cycle.

As indicated in Figures 5.16 and 5.20, sensor S1 can be readily aligned to the OA-OB zero torque position. This can be accomplished by applying a constant current to the OA-OB terminals. The rotor will rotate to the OA-OB zero torque position and then stop. Sensor S1 should then be positioned so that its output just switches from a low to high logic state. Sensors S2 and S3 may then be positioned 120 and 240 electrical degrees respectively from S1 (either CW or CCW direction depending on the direction of rotation) and basic commutation will be established for the motor.

5.4.3.5 Rotor Configurations

The brushless DC motor rotor configurations (Figure 5.21) most often used for scanners consist of rare-earth samarium-cobalt permanent magnets that are contained with a rigid ring or cup for the outer rotor configurations, and are usually bonded to a machined hub for the inner rotor configurations. The inner rotor configuration is generally used at the higher speeds because of the lower centrifugal forces resulting from a reduced rotor diameter.

Owing to the elastic characteristics of epoxy and other adhesives, and the need for stable and reliable precision balancing, the operating speed of DC brushless spinner rotors is generally less than what can be expected for the hysteresis motors. However, DC brushless

FIGURE 5.20

Three-phase motor commutation logic and excitation. (From Axsys Technologies Motion Control Products Division, San Diego, CA, *Brushless Motor Sourcebook*; Axsys: San Diego, CA, 1998. With permission.)

motor technology is steadily displacing other motor types in many high-speed applications. Stainless steel sleeves have been used to aid in the retention of the rotor magnets and improve the rotor mechanical characteristics at high speeds. In addition, ring magnet rotors have been developed for high-speed designs, allowing DC brushless motors to operate in excess of 80,000 rpm. In this rotor configuration, a ring of the rotor material is magnetized by the pole pieces of a powerful electromagnet, which imprints the pole locations and polarities into the ring. This type of rotor design has in fact been employed to drive precision polygonal scanners for laser projection systems which operate at 81,000 rpm.

Pictured in Figure 5.10 is a low-cost, high-speed DC brushless motor, which has been successfully used in several scanner designs. The simple stator design, which allows for machine winding of the coils, and the inexpensive ring magnet rotor, account for the low manufacturing cost of this rugged and reliable motor. The rotor magnet is further strengthened by an outer stainless steel sleeve.

FIGURE 5.21

Brushless DC motor configurations. (a) inner rotor brushless DC motor; (b) outer rotor brushless DC motor. (From Axsys Technologies Motion Control Products Division, San Diego, CA, *Brushless Motor Sourcebook*; Axsys: San Diego, CA, 1998. With permission.)

FIGURE 5.22

Low-speed DC brushless motor.

The commutation sensors (Hall effect devices) are placed within the stator slots and do not require any timing adjustments. This motor is capable of delivering at least 50 W on a continuous duty basis. Also visible in Figure 5.10 is the rotor hub assembly onto which the ring magnet and the optical encoder disc are mounted.

Pictured in Figure 5.22 is a miniature eight-pole brushless DC motor, which is suitable for many low-power scanner drive applications. The stator configuration is noticeably more complex than the low-cost motor pictured in Figure 5.10 and is intended for lower speed applications where cogging torque must be minimized. Commutation of the windings in this design is performed by dedicated channels of a shaft-mounted optical encoder rather than Hall effect sensors.

Commutation timing adjustment is made possible by rotating the encoder pattern relative to the rotor magnet position. Optimum timing at the desired operating speed is required in order to produce the lowest torque ripple and power consumption. The rotor assembly is of a more conventional design, where individual magnet pieces are bonded to a machined hub, which is then ground to the final dimensions.

For low-speed applications it is desirable to construct the motor using the highest pole count possible, that is consistent with the physical size and the electrical parameters specified. The smaller commutation angle and the resulting higher ripple torque frequency may be more readily attenuated by the rotating inertia in the system and produce a more constant speed within one revolution of the rotor.

5.5 CONTROL SYSTEM DESIGN

The basic control requirements for a precision polygonal spinner are to provide synchronization and velocity control for precise scan registration, whether on a film plane or detector array, or at a distant target being illuminated. To this end, the principles of feedback control are utilized for synchronization, velocity, and phase position (shaft angle) control.

In our film recorder example (Figure 5.9), speed control is required for accurate pixel positioning, repeatability, and linearity, as well as line-to-line pixel registration and synchronization. In order to accurately position data pixels in a line at the film plane, the system must generate precision pulses spatially related to the facet angles. These pulses, occurring on a one per pixel basis, are used to gate in and turn off the intensity-modulated video being projected to the light-sensitive film surface. Because there are 120,000 pixels in the film recorder example (12 times 10,000) per revolution, one clock pulse would be required for every 10 arc s of shaft rotation.

Optical encoders are well suited to the task of generating accurately timed and positioned pulses. However, incremental, high-density data track encoders are expensive, large in diameter, and difficult to mechanically interface with an integral spinner/motor/shaft assembly.

To overcome this problem, a smaller and inexpensive low-density optical encoder having 6000 pulses per revolution (PPR) was designed into the system. The required 120,000 PPR pixel clock pulses are obtained by electronically multiplying the encoder data track frequency (6000 PPR) by a factor of 20. Scanner speed control is accomplished by frequency/phase locking the encoder data track (600 KHz) to an accurate and stable crystal oscillator. An index pulse is accurately positioned at the normal of a facet on a second encoder track, thereby providing start of scan (refer to Figure 5.9, SOS detector) synchronization and pixel registration.

This system of generating pixel clock pulses places a heavy burden on the performance accuracy of the rotating shaft assembly, the encoder design and adjustment, and the stability of the crystal oscillator. Nevertheless, the net speed control and jitter performance has been optically measured to be less than ± 10 ppm for one revolution of the scanner.

5.5.1 AC Synchronous Motor Control

Velocity control of the hysteresis synchronous motor is intrinsic to its design, that is, the long-term speed is as accurate as the applied frequency. With reference to Figure 5.14, the stator and rotor fields rotate together (at an integer submultiple of the applied

frequency) with the rotor lagging by the torque angle α and with possible modulations of $\pm\beta$, as was previously discussed. The control systems' task is to fix the rotor vector position, and therefore eliminate hunting and other speed variances.

To implement phase-lock control, the shaft rotational frequency and phase position are measured with a shaft-mounted incremental encoder. The encoder pulses are frequency and phase compared with a stable reference frequency using a frequency/phase comparator, which has the transfer characteristics as shown in Figure 5.23. The frequency/phase comparator has a unique transfer characteristic that allows the device to produce an output that is in saturation until the two input frequencies are equal. This is the frequency detection mode of the phase comparator. The saturation level is either positive or negative in value, and is useful in determining whether the motor speed is too high or too low. Assuming that the motor has reached synchronous speed, the tachometer frequency will equal the reference frequency, and the frequency/phase comparator will operate in the phase comparator mode. In this mode of operation, the output of the phase comparator is an analog voltage proportional to the phase difference between f_T and f_R . At zero frequency and phase differences, the two signals are edge locked, and the phase comparator output voltage is zero. Should the shaft advance or retard for any reason, the phase comparator error voltage will be in direct proportion to the phase difference within ± 360 electrical degrees of the reference frequency.

With reference to Figure 5.24, the phase comparator error is processed through a proportional-integral-derivative (PID) controller compensation scheme and fed to the control input of the phase modulator.

The phase error-corrected phase modulator output frequency, f_M is applied to the motor, thereby completing the position control loop from the encoder to the frequency/phase comparator. The open-loop DC gain of the system is primarily determined by the product of the encoder, frequency/phase comparator, integrator, and phase modulator gains. The high DC gain of the integrator (100 dB) reduces the phase error between f_R and f_T to zero, resulting in near perfect synchronization. The differentiation gain constant provides sufficient damping to eliminate "hunting" and improve the overall dynamic performance and speed regulation to less than 1 ppm.

5.5.2 DC Brushless Motor Control

The velocity control of a brushless DC motor differs from that of hysteresis synchronous in that the brushless motor speed is a function of applied motor voltage, as opposed to

FIGURE 5.23
Phase/frequency detector (comparator) characteristics.

FIGURE 5.24

Control system block diagram, hysteresis motor. (From Marshall, G.F.; Rynkowski, G.A. Eds. *Optical Scanning*; Marcel Dekker, Inc.: New York, 1991. With permission.)

the frequency/phase as the driving function of the latter. The same principles of feedback velocity/position control are utilized in a similar fashion and are depicted in Figure 5.25. The elements within the closed-loop block diagram are essentially the same, with the exception of the motor transfer function and the addition of a DC power amplifier. The DC brushless motor transfer function is shown in detail in Figure 5.26. For simplification purposes, the commutating and pulsewidth modulation circuits have been omitted, but will be covered in a later discussion.

As before, to implement phase-lock control, the shaft frequency and phase position are measured with a shaft-mounted incremental encoder. The encoder pulses are frequency and phase compared with the reference frequency using a frequency/phase comparator, which has the transfer characteristics shown in Figure 5.23. The frequency/phase comparator has a unique transfer characteristic that allows the device to produce an output that is in saturation until the two input frequencies are equal. The saturation level is either positive or negative in value, and is useful in determining whether the motor speed is too high or too low.

The controller will accelerate or decelerate the motor until there is no frequency difference between the reference and the encoder signal. At this point a phase measurement is made by the comparator with every reference pulse cycle and an output voltage is generated that is proportional to the phase error.

The phase error signal is then processed through a PID controller and compensator, similar to that used in the hysteresis motor control system (Figure 5.24).

The detailed DC motor transfer function shown in Figure 5.26 relates the motor angular velocity ω_s to the applied terminal voltage V_T . In English units the constants are defined as (across any two leads for a three-phase delta, or three-phase Y motor): R = motor winding resistance (Ohms); L = motor inductance (Henry); I_M = motor current (Amperes); K_T = motor

FIGURE 5.25
Control system block diagram, brushless DC motor.

FIGURE 5.26
DC motor transfer function block diagram.

torque sensitivity (oz-in/Amp); K_B = motor BEMF constant (Volts/radian/s); J_M = motor moment of inertia (oz-in/s²); J_L = load moment of inertia (oz-in/s²); $T_F + T_L$ = sum of the friction and load torque (oz-in); and F = motor damping coefficient.

As the control system is turned on, the error signal is power amplified, causing the motor to accelerate to a speed at which f_T exceeds (overshoots) f_R . At this point, the error signal reverses polarity, reducing the motor speed until f_T equals f_R . Ultimately, a point of equilibrium is reached at which time the frequency/phase comparator error voltage is zero, and the integrator output voltage regulates the speed of the motor. Furthermore, the high DC gain of the integrator maintains a zero phase difference between f_T and f_R resulting in edge lock synchronization.

To ensure stable and accurate speed control, and to determine the gain coefficients K_P , K_I , and K_A , the motor and load characteristics should be modeled. Several very useful simulation programs such as *SIMULINK* (The Math Works, Inc., Natick, MA) are available for the systems designer which greatly reduce development time by allowing the rapid testing of various control configurations.

In conclusion, the DC brushless motor, when properly designed for the scanning application at hand, is capable of meeting or exceeding the performance of AC hysteresis motors in all but the highest speed applications. All of the successful scanning products that are discussed at the end of this chapter use brushless DC motor technology.

5.6 APPLICATION EXAMPLES

The following sections describe a few of the many scanner designs and control systems that have been developed over the last few years. The overall industry trend reflects the unrelenting drive of the end use market to improve performance, reduce power consumption and size of the supporting electronics, and to reduce the cost of the scanner subsystem.

Fortunately, the consumer electronics and automotive markets have provided many of the electronic components that have proven to be invaluable in the quest to reduce the size and cost of the scanning system. Progress in miniaturization and power reduction of the scanner control electronics is also largely due to the advancements in brushless DC motor technology. As the cost and complexity of the drive electronics for brushless motors approach those of conventional DC motors, brushless motor technology will likely displace all other motor types in scanning subsystems, as it offers high efficiency along with the high reliability, as previously found only in AC motors.

5.6.1 Military Vehicle Thermal Imager Scanner

Pictured in Figure 5.27 is a small 12-facet polygon scanner that is designed for a military vehicle thermal camera system. This compact ball bearing scanner operates at 600 rpm and serves to generate the field scan function in conjunction with an infrared detector array. The motor and control system is designed to maintain polygon speed regulation to within 15 ppm (0.0015%). In addition, the control system must maintain the specified speed regulation in the presence of base disturbances, which are passed to the scanner as a result of vehicle motion. These challenges have been met in this compact scanner by the use of a high-resolution encoder and lightweight polygon design in conjunction with an agile control system.

The scanner employs a small low-voltage brushless DC motor, which is optimized for low cogging torque and smooth operation at low speed. Motor commutation is derived

FIGURE 5.27
Military vehicle thermal imager scanner.

from three dedicated commutation tracks on the optical encoder disk, which also includes a high resolution 3000 count tachometer track as well as an index.

At the center of the control system is a single-chip motor driver, which decodes the commutation information provided by the encoder and produces the correct three-phase motor current waveforms necessary for proper operation of the motor. Motor driver ICs of this type are commonplace devices found in computer disk drive and CD player applications. The motor driver produces a current through the motor windings that is proportional to a command voltage at its input and also incorporates a brake feature that is used to decelerate the motor for better control of the polygon speed under the influence of disturbances.

Tight speed control is accomplished by the use of a phase-lock loop regulation method as described in detail in the previous sections. At the operating speed of 600 rpm, the 3000 line optical encoder produces a tachometer frequency of 30 KHz, which is compared against an externally generated reference frequency in the phase/frequency comparator circuit. Any resulting phase error is amplified and filtered, and then fed to the motor driver, which increases or reduces the motor current to maintain the speed and minimize the phase error. If the motor control voltage falls below a predetermined level indicating that the scanner is operating above the reference speed, then the control system applies dynamic braking to the motor, which quickly decelerates the motor and the polygon.

A block diagram of the controller/driver is shown in Figure 5.28.

5.6.2 Battery-Powered Thermal Imager Scanner

The polygon scanning system pictured in Figure 5.29 was designed for a compact, low-cost, military thermal sighting device primarily intended for small arms applications. Many unique and difficult requirements are imposed by the system specifications on this relatively low-cost device. A wide operating temperature range, precise scanning speed, low cross-scan error, and low power consumption must simultaneously be met. In addition, the scanner must meet the demanding performance specifications for a high-resolution

FIGURE 5.28
Block diagram, military vehicle scanner controller/driver.

FIGURE 5.29
Battery-powered thermal imager scanner.

TABLE 5.5

Battery-Powered Scanner Characteristics

Operating temperature	-40 to +75°C
Polygon speed	600 rpm
Speed jitter (one rev)	15 ppm or less (0.0015%)
Encoder outputs	1500 ppr and index
Input voltage	+10 VDC and +5 VDC
Peak shock level	500 g (0.5 ms)

imaging system while being subjected to severe levels of shock and vibration. Particular attention was given to ensure the mechanical stability of the polygon under severe environmental conditions. Some of the scanner requirements are as shown in Table 5.5.

In order to maximize battery life, the total power consumption of the scanner was limited by the specification to less than 0.4 W while operating in synchronism at the low-temperature extreme.

A compact low-speed brushless DC motor similar to that in Figure 5.22 was designed specifically to address the low power and low cogging torque requirements necessary for this application. A new, single chip motor driver, which employs PWM control, was selected to improve efficiency in the drive and help meet the power consumption requirement. The driver PWM efficiency benefit becomes more apparent as the motor load increases and the drive must supply more current to maintain speed regulation. With a linear motor driver such as the one used in the military vehicle scanner, additional power is lost in the form of heat dissipated in the driver power section.

Effective speed regulation is achieved by the implementation of the same control scheme used in the military vehicle scanner shown in Figure 5.28. The optical encoder tachometer track line density was reduced to 1500 counts per revolution to meet the interface requirements of the imaging system. At 600 rpm the encoder tachometer track produces a 15-KHz pulse frequency, which is at an adequately high rate to maintain precise speed control of the polygon.

The phase-lock loop control system was optimized to maintain phase lock of the encoder tachometer with the synchronization reference under the influence of base motion disturbances and thereby prevent the loss of the image produced by the camera system during movement or under vibration. The need to reject base motion disturbances while providing precise speed control poses a unique challenge in the design of the control system. The scanner total rotational inertia must be minimized to allow the motor torque to accelerate and decelerate the polygon in order to overcome disturbance-induced speed changes. On the other hand, the rotational inertia within the scanner acts to reduce the effect of bearing and motor torque fluctuations, which tend to degrade speed stability. A compromise design was reached that adequately addresses both needs and meets the performance targets set for the scanner.

In order to reduce cost and update the electronic design of the control system, a new controller/driver circuit board was developed, which is shown in Figure 5.30. Significant cost savings were realized as older, ceramic packaged military grade integrated circuits were replaced with industrial quality devices. Performance and environmental specifications for the scanner were met with the plastic-packaged industrial ICs, and the part obsolescence issues were solved that appear with ever greater frequency in the electronic components world.

5.6.3 High-Speed Single-Faceted Scanner

The successful scanner design shown in Figure 5.31 was developed for the publishing and printing industry for use in the image setting machines that are the output devices leading to the manufacture of printing plates. The single-faceted mirror, or monogon, rotates at high speed and scans an intensity modulated laser spot along a sheet of film not unlike that shown in the film recorder system of Figure 5.9. The exceptions are that the film sheet

FIGURE 5.31
High-speed scanner and controller/driver.

usually lies on the inside surface of a cylindrical drum and the $F-\theta$ lens is omitted. Also, the film sheet is stationary and the scanner rides the length of the drum on precision linear bearings driven by a ball-screw mechanism.

For improved speed stability and cross-scan accuracy, as well as greatly improved bearing life, the scanner rotating elements are supported by self-pumping conical air bearings. This type of bearing provides excellent high-speed stability and low friction with the benefit of virtually unlimited operating life. The self-pumping action of the air bearing design is a major factor in reducing the cost of the scanner because an external air supply is not required. Some versions of this scanner operate at 60,000 rpm and utilize the highspeed motor design shown in Figure 5.10. The low-cost optical encoder shown in Figure 5.9 provides up to 2000 pulses per revolution for effective speed control and also sends mirror position information to the imaging system. The success of this scanner design is partly due to the development of a low-cost single card controller, which is described in greater detail in the next section. The scanner and control system block diagram is shown in Figure 5.33.

5.6.4 Versatile Single Board Controller and Driver

The need for a versatile, compact, and inexpensive motor driver and speed controller led to the development of a successful circuit capable of delivering up to 100 W of power to a three-phase brushless motor scanner. All of the functions necessary to achieve precise scanner speed control have been integrated into one unit. The reference frequency generator, phase-lock loop controller, and motor driver are combined on a single low-cost circuit card, which measures 4 × 8 in. A great deal of flexibility has been incorporated into this low-cost controller design so that many scanning applications can be readily accommodated without the need for circuit modifications. Various encoder resolutions and reference frequencies may be accommodated by setting jumpers that reconfigure the digital logic in order to present compatible frequencies to the phase comparator circuit.

FIGURE 5.32

Single board scanner controller and motor driver.

This single board controller has been utilized to drive single-faceted as well as polygon scanners operating between 3000 and 81,000 rpm for a variety of laser scanning applications, and has demonstrated excellent speed regulation capabilities. The rotational speed jitter in many of the air bearing scanners driven by this controller was measured to be only a few parts per million within one rotation. This successful design has been incorporated into thousands of scanning systems sold to the printing and publishing industry worldwide. The controller is shown in Figure 5.32.

As shown in Figure 5.33, the circuit functions can be divided into the following main categories:

1. Reference frequency generator and external sync processing circuit
2. Phase detector and PWM synchronization circuit
3. Control loop PID circuit
4. Brushless motor controller and FET power section

The controller reference frequency generator and external sync processing circuits function to provide a precise and stable frequency reference to the phase comparator. An on-board quartz reference oscillator and programmable divider provide for the selection of up to 16 preset operating speeds for the scanner. The speed may also be continuously varied within a wide band with the application of an external reference frequency from the imaging system controller. In this way, fine adjustments to the scanning speed may be made to trim the system optical parameters.

The phase detector and frequency comparator circuits produce the speed error voltage, which is then amplified and sent to the servo compensation network. The phase detector exhibits high gain since the output is in saturation until the two frequencies f_R and f_T are exactly the same, as discussed previously and shown in Figure 5.23. This feature is responsible for the precise nature of phase-lock loop speed control systems.

FIGURE 5.33
High-speed scanner and controller functional diagram.

Another useful innovation developed in the quest to provide the best possible speed regulation is the synchronization of the PWM oscillator with the phase detector reference frequency. The synchronization of these two frequencies ensures that the noise generated by the beat frequencies do not interfere with the scanner speed control circuits. When synchronized, the two frequencies produce a sum or difference (beat frequency), which will be constant. Stationary beat frequencies may be filtered or appear only as DC offsets, which may be subtracted from the speed control signal. The PID servo controller is similar to the arrangement shown in Figure 5.25 and described in earlier sections. Because most of the scanning systems targeted for this controller are for stable and controlled environment applications, the servo control loop is optimized for speed control regulation rather than response time. In these applications, high rotating inertia in the scanner rotor and polygon is a benefit to speed regulation.

The motor driver and power output section consists of a monolithic (single chip) controller and discrete FET power switches. With a modest amount of forced air cooling, the FET power section is capable of delivering up to 4 A continuously and 6 A for several seconds to deliver higher motor starting current. The motor current is regulated by the driver IC using PWM control, which is effective in delivering power to the motor with minimum heat generation in the controller.

For some high-speed polygonal scanning applications it may not be possible to include an optical encoder within the scanner housing. In this instance, the polygon facet frequency may be used as the speed feedback sensor as depicted in Figure 5.34. The optical pulse frequency should be at or above 1 KHz in order to provide precise speed regulation in this configuration.

FIGURE 5.34
Scanner controller configured for high-speed polygon application.

5.7 CONCLUSIONS

The availability of low-cost brushless DC motors and drivers has made a significant impact on rotary scanner designs over the past 15 years. Advances in the motor driver area have been especially important in that the size and cost of these devices have been reduced remarkably. The power efficiency of brushless DC motors as well as the motor driver allows for high mechanical power output with minimal temperature rise. For many polygon-scanning applications, it is now practical to integrate the drive and control functions directly on the scanner or motor body.

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