Application of Rotary Optical Encoders and Resolvers in Brushless Servo Motors

Robert Setbacken
RENCO ENCODERS, INC.

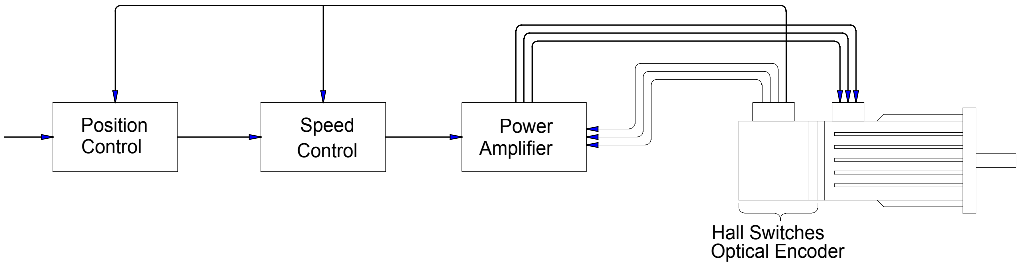
The trend toward wide scale use of Brushless Motors is being driven by manufacturing cost reductions, improved efficiencies, greater reliability, availability of improved drive electronics, and the availability of improved sensors for motor control. This paper discusses the application issues associated with the use of resolvers and optical encoders as the primary feedback element on a BLDC Servo motor.

System Configurations. For the majority of applications in the US and Japan, the trend in brushless motor sensor designs is moving away from Hall boards and feedback elements to
integrated devices. For resolver applications, it can be handled by adding a dedicated set of 2, 3, or 4 speed windings for commutation, or it can be handled with a single speed winding and an intelligent drive. For Encoder applications, system designers are choosing encoders with integrated commutation outputs in addition to data channels. Figures 1, 2, and 3 show the basic configurations for systems using these approaches.

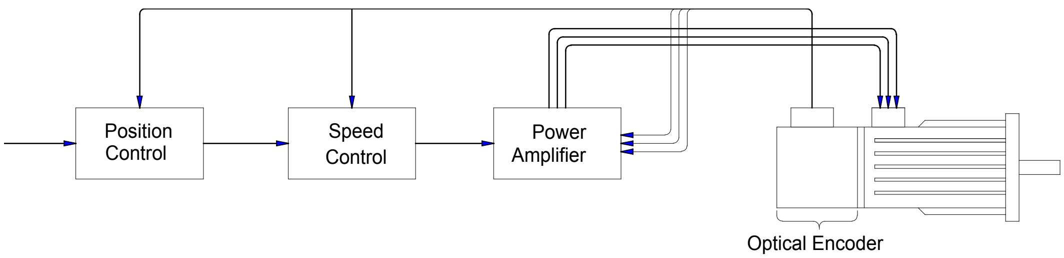
The elimination of the Hall sensors from the BLDC motor eliminates many of the potential problems which can occur in a motor application. Hall devices are sensitive to acoustic noise, current spikes, temperature, EM fields, and can be difficult to align, which results in torque ripple. When a BLDC motor is used in a servo application with a high resolution feedback sensor, Hall sensors are redundant and consume space. They also add to motor length, assembly costs, cable harnessing complexity, and decrease overall reliability. The use of an encoder or resolver to eliminate Hall sensors in this situation is not only cost effective, but also improves the overall system performance.

Encoder Types. When an encoder is used as the feedback element, there are a variety of types to choose from. The following is a short summary of the predominant types currently available.

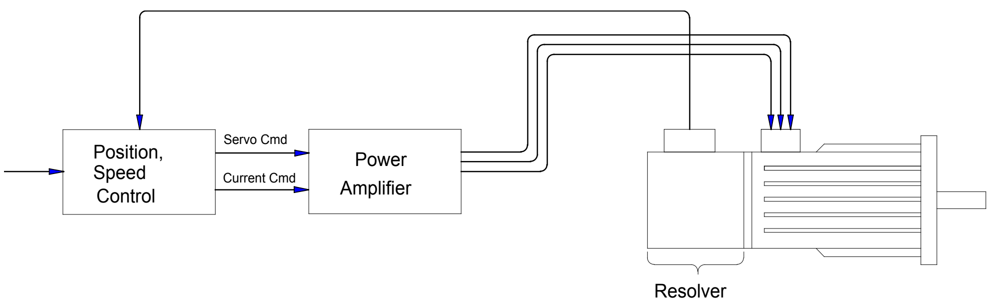
1. <u>Incremental, (TTL)</u>
   Readily available from a wide variety of Suppliers. Almost unlimited line count availability up to 5000 cycles per revolution. Special line counts and output options are easily obtained.
2. <u>Incremental with Commutation, (TTL)</u>
   Becoming more common in the US and Japan, availability is somewhat constrained by lack of industry standards. Mounting configuration, signal conditioning, and power supplies vary widely. Available in line counts up to 8000 for 2, 4, 6, and 8 pole motors. They are being developed in both hollow-shaft and modular versions by a variety of encoder suppliers.
3. <u>Incremental with Commutation, (Sine wave)</u>
   More common in Europe, this type of encoder generally has sinusoidal quadrature outputs, with a 1 volt pk-pk amplitude. Commutation is accomplished using a quadrature one cycle per revolution output.
4. <u>Absolute Single Turn, (TTL/Parallel)</u>
   Less common for drive applications, these are usually found in 10 to 12 bit versions. Larger word sizes are available, but costs become a real issue and make them unsuitable for all but the most specialized applications.



Drive with Hall board, Encoder or Resolver for Commutation and Feedback
Figure 1



Drive with Commutating Encoder
Figure 2



Drive with Resolver Feedback
Figure 3

5. <u>Absolute Multi-turn, (Sine wave Incremental, Serial Absolute)</u>
These encoders are generally based upon a 12 or 13 bit single turn absolute encoder, with a 12 bit turn counter yielding 24 or 25 bits of position information. Although these have been available for some time, they have been too costly for widespread applications. Recent developments in Europe, however, are making these more available, and costs are starting to come down. These encoders contain an incremental output with A, B, and Reference pulse, a serial absolute interface, and commutation outputs. Commutation output is derived from the MSB of the single-turn absolute. The Incremental tracks are derived from the LSB of the absolute encoder, and generally result in a 2048 or 4096 cycles per revolution incremental signal that is suitable for use in high-speed servo controls.

Resolver Types. The world of synchros and resolvers has an even wider variety of available configurations, some branching into the esoteric and not really relevant to this discussion. For BLDC servo applications, the primary sensor used is the brushless resolver, and these are either housed units or frameless. Housed units are mounted in an endbell with a coupling, while frameless units are mounted directly to the motor shaft.

Motor/Sensor Packages. The sensor configuration chosen depends ultimately upon the intended application. Cost is always an important issue, and for BLDC motors, there appear to be five categories of applications.

1. Low Cost motors for basically constant speed operation. Typical examples are fan motors, fuel pumps, disk drives. These are very high volume, low cost applications where tooling of molded magnets and Hall structures can be justified. Alternatively, many are doing away with Hall sensors and going to smart IC controls. Control chips made by Allegro Microsystems, Inc., Hitachi America Ltd., Micro Linear Corp., Signetics Co., Silicon Systems Inc., SGS-Thomson Microelectronics, Inc. can provide complete commutation of BLDC motors. Some of these controllers even provide braking and speed control as part of the package, so an external sensor like an Encoder or a Resolver is not needed for this type of servo application.
2. Traditional BLDC motors with Resolver feedback or Encoder feedback. These are motors which contain an Encoder or a Resolver for position feedback, and possibly a Tachometer as well depending upon the control system being implemented. Encoder-based systems also require Hall sensors for commutation. Resolver systems used with a "Rectangular" Drive could use Hall sensors as well, but this is usually not done in practice. For Sinusoidal Drives, resolver feedback is usually all that is needed. These types of motors have been the backbone of the BLDC motor industry for the past decade and are found in a wide variety of applications.
3. Integrated Sensor Motors. These motors use optical encoders which generate rotor position signals in addition to incremental position. The rotor position signals are electrically the same as can be obtained from Hall switches, and can be used for commutation of 2, 3, or 4 pole-pair motors. Integrated Sensor BLDC motors are being used in Japan and the US to provide high performance servo drive solutions to cost critical applications. The encoders are "built-in" hollow shaft encoders, and generally come in resolutions up to 13 bits (2^{13} = 8192 cycles per revolution.)
4. High Performance Integrated Sensor Motors. These motors are used in systems requiring large dynamic range in the speed control, i.e. Z-axis in a machine tool, very high resolution, or very low speed operation. These are being developed primarily in Europe and are distinguished by the output signals being sinusoidal rather than TTL.
5. Smart Motors. These are High Performance Integrated Sensor Motors requiring additional capabilities, such as absolute position, bus interfaces, storage for motor data, temperature monitoring, etc. This is currently a very small portion of the market, but is definitely growing. The sensors for these motors provide commutation outputs, incremental outputs, and up to 25 bits of absolute position data, 13 bits per turn, with 12 bit turn counting.

System Issues - Anyone in the Manufacturing business today is being asked to lower costs, improve quality, and increase performance. The rotary encoder industry is actively involved with motor manufacturers in development of new products to meet this challenge. The development of a motor/sensor package must consider a variety of issues, and the following list discusses some of the most important issues.

1. Absolute vs. Incremental Position. Resolvers provide absolute feedback. In cases where absolute position information is needed, e.g. for robotics applications, a resolver can be a good choice. Rotary Encoders can provide either incremental or absolute outputs, and in fact, most absolute encoders now provide both. The need for absolute or incremental position information is generally application dependent, and many drive systems can develop or handle either type of interface.
2. Cost. The costs of a motor/sensor assembly depends upon the manufacturing approach, volume produced, and intended application or operational environment. Resolver based systems depend heavily upon the cost of the interface electronics, and whether the manufacturer has an in-house solution or is dependent upon a chip manufacturer. (Analog Devices, DDC, etc.) Typically, the cost of a resolver installation, including interface IC's and support components, is between $110 and $150. Encoder based systems are a bit more flexible in this area, at least for the TTL output versions. These systems allow users to exploit very low cost interfaces, and the standardized output formats make these types of encoders almost a commodity item. This allows the motor/drive manufacturer to shop encoder manufacturers quite readily, and in some cases can result in encoder based systems costing as much as 30% less than Resolver based systems[1]. When using encoders with integrated commutation outputs, the cost of an encoder solution can become even more cost effective. However, most cost comparisons set a resolver, an absolute device, against an incremental encoder. Although the encoder cost may in fact be less in this situation, when comparing a resolver to a single-turn absolute encoder, the cost situation reverses. The motor manufacturer must work to balance the costs of sensor interface to sensor technology in the way that best suits the application, the intended market, and the capabilities of the manufacturer. However, recent developments in Europe may swing system costs dramatically, and are targeted at virtually eliminating the cost differences between resolvers and encoders. The VECON Project, being managed by the Institute for Applied Microelectronics, will soon have a two chip set that will implement the entire drive electronics for a BLDC motor. With a planned cost of $55, the chipset will accept sine-wave commutation signals, incremental encoder and resolver inputs, and have an SSI interface for communication with Absolute encoders. When components of this capability become available, system cost will depend exclusively on performance requirements.
3. High Speed Operation. Any system, encoder or resolver based, will generate data based upon the resolution of the sensor, multiplied by the interpolation factor of the interface electronics. For most resolver based systems, the feedback element is a single speed device, providing one cycle of output per revolution, and so is an "Absolute" position device. Because the position information is produced by amplitude modulation of a carrier signal, it usually needs to be converted to a digital format before it can be used by a motor controller. Resolver-to-Digital Converters, (RDC), "interpolate" the resolver output signals and provide 10, 12, 14, and 16 bit results, depending upon the converter used. (Some even have software programmable word sizes.) When coupled to a 12 bit RDC, a position measurement resolution of 360°/4096 or 5.27 minutes is obtained. The frequency this conversion must be obtained at depends upon the rpm of the motor, and Table 1 shows this relationship. For example, a 12 bit RDC must be able to present a conversion result

[1]Manolis, Steve, "Resolvers vs. Rotary Encoders", Motion Control, March 1993 Vol. 4, No. 3

	Cycles per Revolution						
rpm	1	128	256	512	1024	2048	4096
3000	0.1	6.4	12.8	25.6	51.2	102.4	204.8
4500	0.1	9.6	19.2	38.4	76.8	153.6	307.2
6000	0.1	12.8	25.6	51.2	102.4	204.8	409.6
7500	0.1	16.0	32.0	64.0	128.0	256.0	512.0
9000	0.2	19.2	38.4	76.8	153.6	307.2	614.4
10500	0.2	22.4	44.8	89.6	179.2	358.4	716.8
12000	0.2	25.6	51.2	102.4	204.8	409.6	819.2
13500	0.2	28.8	57.6	115.2	230.4	460.8	921.6
15000	0.3	32.0	64.0	128.0	256.0	512.0	1024.0
17500	0.3	37.3	74.7	149.3	298.7	597.3	1194.7
18000	0.3	38.4	76.8	153.6	307.2	614.4	1228.8

Output Frequency (KHz)
Table 1

at the rate of 200 KHz, or 5 μsec, when the motor is turning at 3000 rpm. The maximum slew, or tracking rate, of an RDC is limited to 1/16th of the resolver reference frequency. For example, the Analog Devices AD2S80A RDC, using a 400 Hz reference, will have a tracking limit of 1500 rpm. This value can be increased to 18,750 rpm using a 5 KHz reference. When the tracking rate of the converter is exceeded, the position value cannot be computed fast enough to keep up with the input, and ".. the digital output will become totally unpredictable."[2] A similar condition exists if the maximum acceleration rate is exceeded.
For an encoder, the tracking rate is limited primarily by the frequency response of the sensor. Low to intermediate cost encoders generally have a maximum frequency response capability of 200 KHz, there is no reference frequency dependency. Newer product offerings are beginning to push the envelope up to approximately 400 KHz, which allows a 4096 cycle per revolution encoder to turn at 6000 rpm without missing counts. Higher performance is available at higher cost, with a maximum frequency response capability of approximately 1 MHz.

4. <u>Low Speed Operation.</u> Low speed operation requires high resolution and accuracy from the sensor. Encoder systems have dealt with this in a number of ways in the past, with new ideas and approaches being limited by available technology until recently. Many encoder-based BLDC systems have simply compromised by using a resolution based upon the maximum rpm and frequency response capabilities of the encoder, then letting the system designer deal with low speed operation via drive-train design. For example, many drives use a 2000 cycle encoder with a 200 KHz frequency response capability. This allows the motor to run at 6000 rpm without missing counts. However, for a digital drive system with a 400 μsec sampling interval, the one increment per sample speed would be 18.75 rpm. It is obvious that the system could run slower, but control accuracy will degrade from this point. Improved low speed operation is usually obtained using interpolation electronics, which use encoder signals that are sinusoidal, like a resolver. Taking advantage of the relationship:

[2] "Synchro and Resolver Conversion", Edited by Geoffrey S. Boyes, Analog Devices, 1980

$$\sin(\alpha+\phi) = \cos(\alpha)\sin(\phi) + \sin(\alpha)\cos(\phi),$$

the base sinusoidal signals $\sin(\alpha)$ and $\cos(\alpha)$ are multiplied by phase shifted copies. For example, a 5X interpolator would use five sets of signals, each shifted 18°. The results are converted into square waves via comparators, and all of the outputs routed through an exclusive OR gate. The result is a set of square waves in quadrature at a frequency equal to five times the original. There are many types of interpolation electronics, and interpolation values of up to 4096 times the base resolution can be obtained, allowing encoder users to develop extremely high count per revolution values. Table 2 shows how this can be obtained. A 2048 cycle encoder paired with 512 times interpolation electronics, yields over a million cycles per revolution. Using the previous example, the minimum controllable speed now becomes 0.0006 rpm.

Interpolation	Line Count					
Factor	256	512	1024	2048	4096	5120
256	65536	131072	262144	524288	1048576	1310720
512	131072	262144	524288	1048576	2097152	2621440
1024	262144	524288	1048576	2097152	4194304	5242880
2048	524288	1048576	2097152	4194304	8388608	10485760
4096	1048576	2097152	4194304	8388608	16777216	20971520

Effective Resolution of Interpolated Encoder Output Signals
Table 2

The result is that encoders are very good for controlling axes at slow speeds, e.g. on the Z-axis of a machine tool, where very high resolutions are required to close the speed loop. Resolver users have similar capabilities, but not to the same degree. Many RDC circuits allow for software programmable resolutions, and tracking rates are resolution dependent. As an example, the AD2S80A has programmable resolutions of 10, 12, 14, and 16 bits. A 16 bit position resolution used with a 400 μ sec sample interval would allow a minimum speed control of 0.038 rpm.

5. Dynamic Range. From the above discussions, it can be seen that the two sensor types can utilize system software to realize a substantial dynamic range. For typical resolver systems, a maximum dynamic range of 18,750 to 0.038 RPM, (113 dB) can be achieved. For encoder systems, using a 4096 cycle baseline device, a maximum dynamic range of 15,000 to .0006 RPM (144 dB), can be obtained.
6. Integration Issues. In order to obtain the above dynamic ranges, both systems require some gymnastics on the part of the designer. The RDC system requires switching of gain resistors in order to switch resolutions, and the encoder must switch to the interpolation outputs for low speed operation. Both situations require thought on the part of the system designer to assure the transfer is "bumpless". In addition, high speed operation of resolver systems generally require higher reference frequencies. Whether this is an acceptable configuration depends upon the system and the application. For a retrofit or refurbishment situation, it may be that the reference frequency and voltage is already set, thus constraining the upgrade possibilities. In the past, 400 Hz or 60 Hz at 26 or 115 volts RMS references have been used extensively, with occasional 1200 Hz applications. Today, it seems that users are moving towards higher frequencies and lower voltages in order to obtain higher tracking rates. The result is that there will be many

opportunities for low level modifications in most refurbishment applications, as references are not standard and probably never will be. New drive systems must also be able to accommodate this as well, resulting in added complexity. Another point to consider is overall power consumption. A typical RDC chip alone will consume 300 mW typ[3], and the resolver will consume more, depending on its design, reference frequency, etc. Typically, a resolver will require approximately 1000 mW.[4] Encoders with commutation included will consume approximately 950 to 1030 mW, depending upon the manufacturer and temperature rating of the encoder.

7. Efficiency. Maximum motor efficiency is obtained when field switching is done accurately. Single cycle sine wave type commutation signals generally have accuracies to about 5° mechanical. Hall switches are in the same range, and are typically very difficult to align. Resolver and Optical encoder commutation can be good to ±10 arc-min. with some careful planning, and are very simple to align.
8. Accuracy. In general, optical encoders have an advantage in this area. Although specially fabricated resolvers can be obtained which are accurate to ±2 arc-min., in general, resolvers have accuracy ratings of ±2 to ±20 arc-min. The corresponding RDC adds an uncertainty of ±2 to ±8 arc-min. plus 1 LSB[5]. Resolver errors also have both static and dynamic contributions, which result from the acceleration error in the RDC tracking loop, offset voltages that are uncompensated, phase shift between the signals and the reference voltage, and Capacitive or inductive crosstalk between the resolver signals and the reference cabling. Noise in the interconnect or on the reference will generate speed dependent errors proportional to the phase shift in reference and inversely proportional to the reference frequency. A quick metric is 20 degrees at 20 rps = 5 minutes at 5 KHz.
   Modular incremental rotary encoders usually have an accuracy rating of 2 arc-minutes or better over all operating conditions. Bearing system encoders are usually 1/20 of a cycle. For a 2000 count encoder this can be as low as 32 arc-sec. Typical plots for accuracy of a modular encoder are shown in Figures 4 and 5.
9. Torque ripple. Torque ripple can result in surface finish irregularity in a machine-tool application and so is generally considered to be a meaningful measure of drive quality and performance. Sine wave motor/commutation systems can have zero torque ripple and are preferred, but costly. Resolvers and encoders can both be used for this type of drive, at about the same cost. Block commutated motor/encoder systems can be lower in cost, and overall performance of a rectangular drive can be about 95% of a sine wave drive. Torque ripple of an open loop system will be higher for a rectangular drive, approximately 13%, but when a closed loop system is implemented, this will be lower. Once again, the system designer must weigh the costs to develop the right system for the application.
10. Reliability. Reliability depends upon the application environment, the overall temperature of operation, the shock, vibration, humidity, etc. Because Modular Encoders do not have bearings, they have a higher reliability rating than bearing encoders. Resolvers also have excellent reliability due to the lack of electronics in the high temperature motor environment. However, most encoders operated at 110°C or lower have life expectancies of 10 years of more.

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[3] ibid. Features, page 1

[4] Synchro and Resolver Engineering Handbook. Clifton Precision, Clifton Heights, PA. 19018 (215)622-1000

[5] Analog Devices, 1992 Data Converter Ref. Manual, Vol. 1, pg. 3-69, S/D Converters, Rev. A

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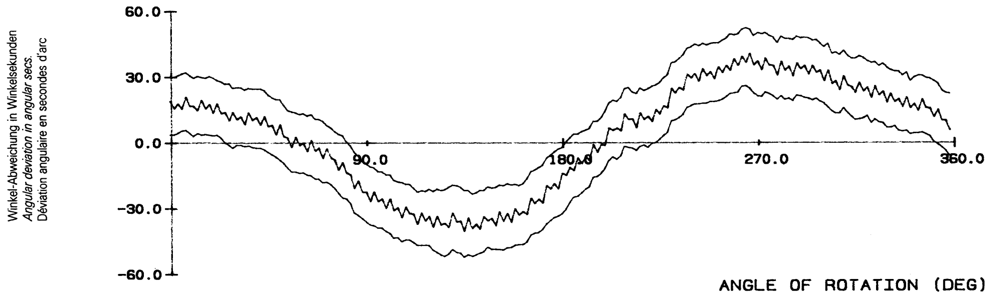
DR. JOHANNES HEIDENHAIN GmbH
D-8225 Traunreut · Tel. (08669) 31-0

Meßprotokoll	*Calibration Chart*	Procès-verbal d'étalonnage	
Drehgeber	*Rotary encoder*	Capteur rotatif	RM15D-1250-1/4
Strichzahl	*Line count*	Nombre de traits	1250
S.Nr.	*S.No.*	S.Nr.	SECOND MOUNTING



Die gemessenen Abweichungen liegen innerhalb der gezeichneten Kurven	*The measured deviations are within the displayed curves.*	Les écarts mesurés se trouvent à l'intérieur des courbes représentées	○
Die Meßkurve zeigt Mittelwerte aus Vor- und Rückwärts-Messungen	*The measuring curve shows average values of bidirectional measurements.*	La courbe de mesure montre des valeurs moyennes de mesurés avant/arrière	○
Anzahl der Meßpositionen	*Number of measuring positions*	Nombre de positions mesurées	1000
EXE	*EXE*	EXE	
Kupplung	*Coupling*	Accouplement	
Datum/Prüfer	*Date/Checked by*	Date/Contrôleur	21.1.1994

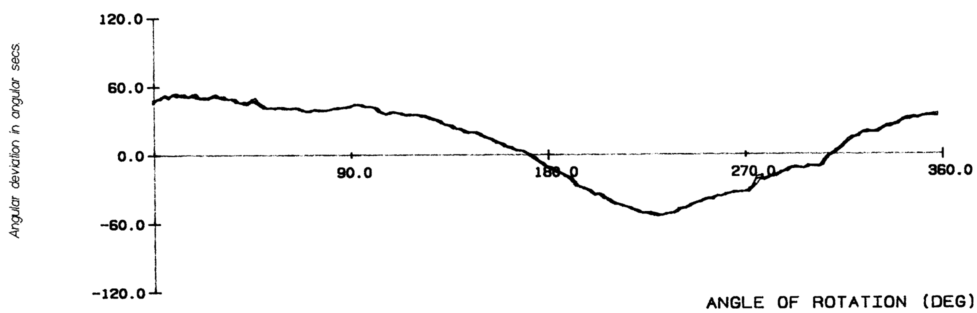
206 492 93

Figure 4

RENCO

Calibration Chart

Rotary encoder	RM15D
Line count	1000
S.No.	7



The measured deviations are within the displayed curves.	○
The measuring curve shows average values of bidirectional measurements.	○
Number of measuring positions	1000
EXE	
Coupling	
Date/Checked by	1.2.1994

Figure 5

11. Complexity. Resolvers are infinitely tunable devices. The user must carefully consider a number of parameters and select fixed components in order to successfully utilize a resolver in any given application. The minimum resolver application must consider reference frequency, bandwidth, maximum tracking rate, number of bits in the conversion result, input filtering, AC coupling of the reference, phase compensation of the signal and reference, and offset adjustment. All of these issues will affect the overall accuracy and performance of the installed device. In contrast, the designer choosing to utilize an incremental or absolute encoder in his system is faced with only two issues, line count and the maximum rpm/frequency response rating. Many encoder designs can now provide data at up to 1 MHz. This would allow a 4000 line encoder, equivalent to a 12 bit RDC, to turn at 15000 rpm. There are also no encoder dynamics to deal with, and the digitization process in an encoder eliminates any analog considerations on the part of the user. Encoders provide data with guaranteed signal separation and symmetry at up to the rated speed, and that is all there is. The added flexibility of interpolation at low speeds is similar to what is done via a multi-speed resolver, but can be implemented at a much lower cost.
12. Bandwidth, Frequency Response. Most RDC's are tracking converters, which are implemented using a type two servo. A type two servo is a closed loop control system which is characterized as having zero error for constant velocity or stationary inputs. Conversely, this type of system will demonstrate errors in all other situations, and the magnitude of these errors must be controlled through optimized "tuning" of the converter. The fact that the converter itself has dynamics becomes an important part of the system design. Being type two, the converter can introduce up to 180 degrees of phase lag into the system. For a 12 bit converter using a 400 Hz reference[6], the RDC bandwidth (-3 dB point) will be less than 100 Hz. Using the same reference, a 14 bit converter will have a bandwidth of 66 Hz, and a 16 bit converter will have a bandwidth of 53 Hz. A 100 Hz -3 dB bandwidth means that there will be approximately 3 dB of peaking and 45° of phase shift at 40 Hz. As many servos attempt to close position loops near these frequencies, an added 45° phase shift would be undesirable. It should also be noted that, although the RDC tracking rate may not be exceeded, a system with difficult load dynamics could well prove unstable when the RDC dynamics are introduced. The situation only worsens when 14 bit or 16 bit converters are utilized.
13. High-Temp Operation. It is common knowledge that resolvers are capable of operating at high temperatures, and in many cases can be operated at up to 150°C. The question is, how useful is this? In many high performance applications, it is the motor winding that is the limiting factor. The feedback device is usually mounted at the end of the motor, and in many applications is thermally isolated to some extent. As a result, it is usually not necessary to require a feedback device to be operated above 100°C, and this temperature can be met by many modern encoders as well as resolvers.
14. Durability. No one can discount the sturdiness of the resolver. It is a simple device with a similar make-up to the motor, consisting of windings, bearings, and sometimes even has brushes. However, for the majority of the environments

[6]Analog Devices AD2S80A, Variable Resolution Monolithic Resolver-to-Digital Converter, product specifications pages 11 and 12

encountered, an encoder is completely adequate. Typical specifications for vibration, shock, and temperature quoted by a variety of manufacturers can be summarized as shown in Table 3. Because both encoders and resolvers can be purchased with or without bearings, neither can claim an advantage in this respect; however, frameless resolvers may have slightly less sensitivity to axial play than a modular encoder would. With respect to electronics, it is true that the resolver electronics can be mounted remotely from the motor, in a less extreme environment. However, they are much more complex than those of the encoder. Typical encoder designs use a small number of very basic components, and can be implemented using commercial, industrial, or military rated devices. It is possible that for extremely high impact shock environments, a resolver could claim some advantage over an encoder. However, if resolutions of less than 1000 counts per revolution are desired, then an encoder with a metal or mylar code wheel can compete favorably with resolver designs.

	Encoder	Resolver
Vibration	15g 10-2000 Hz, 3 axes	same
Shock	50g 11 milliseconds duration	same
Temperature	-10°C to 100°C	-55°C to 125°C

Environmental Specifications
Table 3

Summary
There are many issues involved in selection of the proper feedback element for a motor drive system and they are all interrelated. Some generalizations can be made however.

1. The cost differences between resolver and encoder based systems seem to be vanishing. The desired technology is now the deciding factor.
2. Resolvers seem best suited for very high temperature applications where accuracy requirements are in the 10 to 20 arc-min range.
3. Encoders are capable of very high accuracy and have a simpler, more robust system interface. This may be important in high EMI environments.
4. Encoders have temperature limits in the 100°C region for reasonably priced industrial devices. Higher temperature devices (125°C) are available at a premium.
5. Encoder based systems have a well established technology path for retrofit and upgrades. Resolver based systems tend to be more fixed and immutable once delivered.
6. The dynamic performance of a resolver and the RDC must be considered in a control system design. This is not necessary when using encoders.