Sensing the Motion:

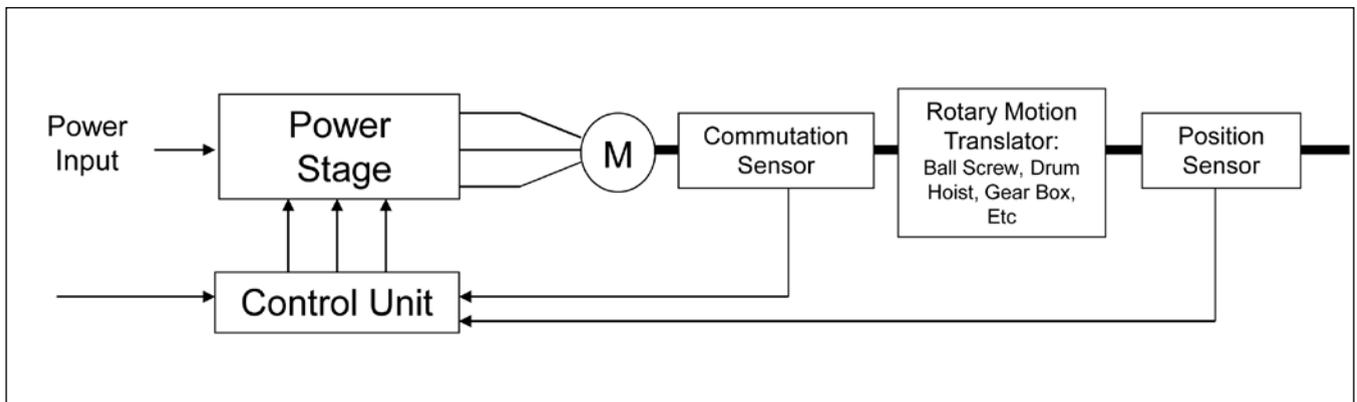Figure 1—Examples of "macro" motion control applications.

Figure 2—Block diagram of typical actuation system.

Rotary Position Sensors—
ELECTROMECHANICAL, ELECTRONIC AND FIBER OPTIC

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Management Summary

Motion control requires feedback. Without feedback, there is no controlled motion. Position sensors are a key element of a motion control system, regardless of whether the primary power is hydraulic, pneumatic or electrical. There are a multitude of position feedback sensor options that reflect a very broad range of technologies—from electromechanical to electronic to optoelectronic to state-of-the-art fiber optics. Design decisions are usually based on a multitude of factors—including environmental, reliability, redundancy, safety and reliability. These applications can also reflect a preponderance of conservatism versus state-of-the-art in a spirited clash of the old school versus new school of engineering.

This paper provides an overview of the more common position sensor options and references actual case studies to illustrate the diverse solutions available and the reasons behind some of the decisions. Three cases are used to illustrate the needs of different applications leading to the choice of a particular type of position sensor. The cases reviewed include a gantry crane, wind turbine and aerial cable car.

Introduction

The world of "macro" (a.k.a. large-scale) power transmission and motion control offers special engineering design challenges because of the sheer size and loads of the mechanisms and structures. The following list of examples characterizes the diverse range of applications and operating environment extremes that can be encountered:

- Cranes
- Aerial cable cars
- Retractable stadium roof
- Leaf, lift and rotary bridges
- Oil drilling rigs
- Tank turrets
- Satellite antenna positioning systems
- Aircraft flight actuators
- Wind turbines
- Ship propulsion systems
- Space station solar panels

Figure 2 illustrates a typical closed-loop motion control system. A typical system consists of these features:

- Motor or actuators can be electric, hydraulic or pneumatic.
- Commutation control of an electric motor can be accomplished via position sensor or sensorless V/I feedback. Sensor-based feedback tends to provide more precise control.
- Actuation usually requires converting rotary motion of a motor to the linear or angular motion required of the structure. For example, a crane's hoist lifts or lowers a cargo container while a wind turbine must be rotated to accurately face the wind.
  - External position sensor allows direct monitoring of the position/speed independent of the feedback sensor used for directly controlling the motor. However, some applications can use one sensor for both controlling the motor as well as monitoring the position of the structure.

The options available for position/speed sensors cover a wide range of technologies, performance and technical maturity. Electromechanical solu-

tions (requiring no external electronics) include discrete limit switches and geared cam switches. Electrical and electronic solutions include resolvers, magnetic Hall sensors, optical proximity sensors and digital encoders. State-of-the-art fiber optic encoders offer the advantages of passive operation (no local power supply required), EMI immunity (like limit switches), superior environmental performance (like resolvers) and ability to operate over extremely long distances (the reason why telecommunication networks use fiber optics for long-distance communications). Systems may also implement a hybrid, integrated solution; for example—combining encoders for advanced motor drive speed control along with electromechanical limit switches for fail-safe backup alarms. In any case, the decision making process should consider total life-cycle costs (including purchase price, operating costs, reliability and potential repair/replacement costs) as well as the customer's technical "comfort zone."

We will use three real-world applications to introduce the different types of position sensors and put some of the decision making issues into context: a cargo crane, wind turbine and aerial cable car. Then we will summarize the various sensor technologies and compare their advantages and disadvantages.

Case #1—gantry crane and geared limit switches. Cranes and hoists are traditional users of rotary limit switches. Cam switches are the most basic and direct form of discrete position feedback or fail-safe backup control. No electronics to power. No computer to program. No software to maintain. Unaffected by EMI or lightning. Simple, rugged, robust and reliable. As shown in Figure 3, cams are mechanically programmed to physically activate/deactivate one or more microswitches corresponding to specific payout positions of a cable wound around a motor-driven drum. Typical applications include chain- or cable-driven drum hoist mechanisms used on lift bridges, dam gates, cranes and hoists.

The gantry crane shown incorporates two degrees of motion: the up-and-down motion of the hoist and the linear movement from ship to truck trailer along the gantry rail. For this example, let's just consider the critical upper- and lower-end limits of the hoist. The hoist position is controlled by a heavy-duty steel rope that pays out from a rotating drum. The rotary limit switch is direct-coupled to the drum shaft with an internal gear reduction corresponding to the number of drum revolutions corresponding to full payout of the cable. Let's assume that 100 turns of the drum corresponds to 100 feet of hoist travel (one turn of the drum corresponds to 1 foot of hoist movement). Thus, the selected gear reduction of the limit switch is 100:1, so that 100 turns of the input shaft corresponds to one full turn of the cam.

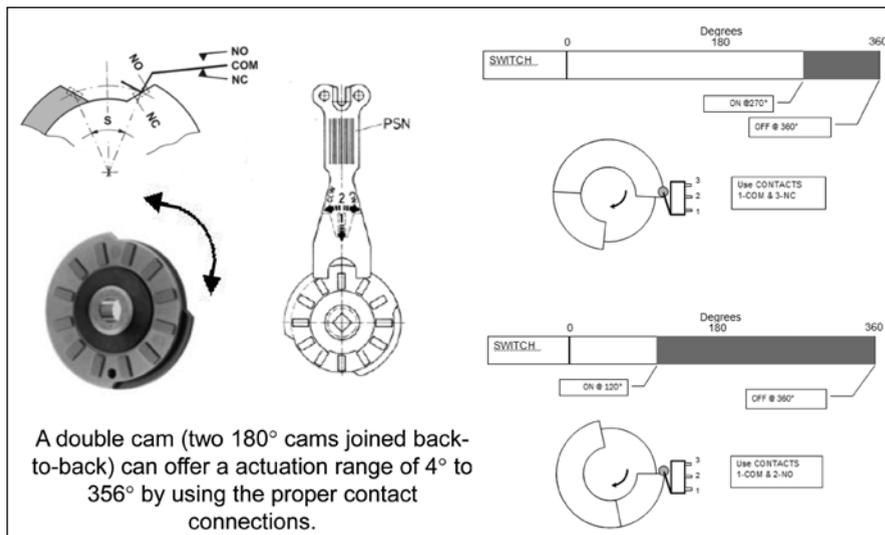Keep in mind for safety reasons that the hoist should never hit the ground

Figure 3—How a rotary cam switch works.

Figure 4—Gantry crane motion and inside view of geared limit switch.

Figure 5—Diagram and examples of resolvers.

or rise above a certain limit that would overrun the top of the hoist. For a lower limit of 4 feet (about one-half container height), we would set the lower-limit cam switch to activate at 4 turns—also corresponding to the 150 (4/100 x 3,600) cam position. For an upper limit of 80 feet, the upper-limit cam switch would be set to activate at 80 turns or 2,880 cam position (80/100 x 3,600).

Case #2—wind turbine and combination yaw/cable twist sensor. The wind turbine yaw mechanism is used to turn the wind turbine rotor against the wind. To generate power efficiently, it is critical that the wind turbine be positioned perpendicular to the wind. Remote wind sensors feed the yaw motor controller with real-time information while the yaw sensor provides real-time feedback of its position. Continuous-position feedback could be supplied by either a resolver or encoder.

Which should be selected?

A *resolver* is a rotary transformer where the magnitude of the energy through the resolver windings varies sinusoidally, as the shaft rotates. As shown in Figure 5, a resolver control transmitter has one primary winding—the reference winding; and two secondary windings—the SIN and COS windings. The SIN and COS windings are mechanically displaced 90 degrees from each other. In a brushless resolver, energy is supplied to the reference winding (rotor) through a rotary transformer. A resolver requires an external R/D (resolver-to-digital) interface.

An *optical rotary encoder* is an optoelectronic device used to convert the angular position of a shaft or axle to an analog or digital code. The optical encoder's disc is made of glass with transparent and opaque areas. As shown in Figure 6, a light source and photo detector array read the optical pattern that results from the disc's position at any one time. This code is read by an embedded processor to process encoder signals and a digital output. There are two types of optical rotary encoders: incremental and absolute.

An *incremental rotary encoder*—also known as a quadrature encoder or a relative rotary encoder—has two outputs, i.e., quadrature outputs. These A and B quadrature outputs are 90 degrees apart. The resolution of an incremental encod-
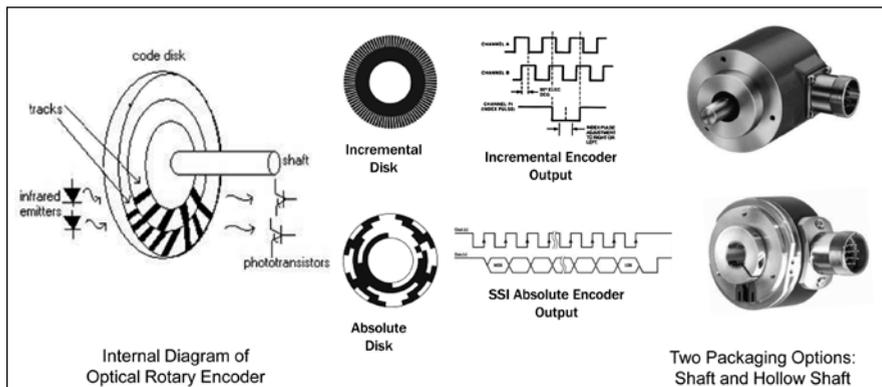

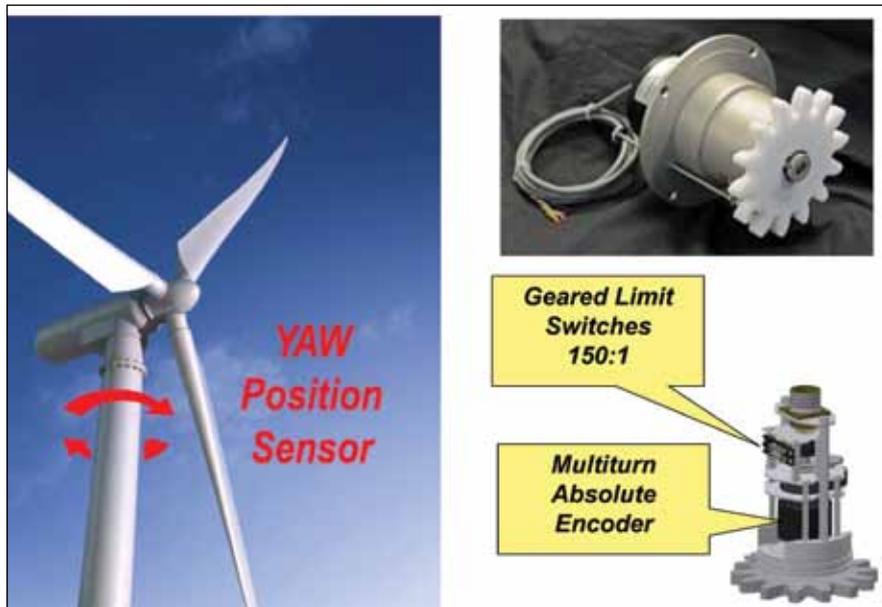Figure 6—How an optical rotary encoder works.

Figure 7—Multifunctional yaw position sensor for wind turbine application.

er is expressed in pulses-per-revolution (PPR) and can range from 100 PPR to as high as 100,000 PPR in some high-resolution models. Optionally, there can be an index (Z) output that provides a reference position corresponding to one PPR. The motor drive or actuator system can count pulses (from an initial reference point) to determine position and measure the time between pulses to determine shaft speed (RPM).

An *absolute rotary encoder* incorporates a glass code disc that contains a binary or gray code scheme that provides a unique output for any position. An embedded processor reads this code and provides either an analog or digital output. The digital output can be parallel, *RS485* serial, *SSI*, *Profibus*, *CANopen* or other type of field bus interface. Analog output can be either 0–10V or 4–20mA. Since absolute encoders are not ideal for speed control, special models also offer an A/B incre-

mental track option.

A particular wind turbine design required two yaw sensor functions—yaw angular position *and* cable twist alarms. The latter prevents the internal power cables from over-twisting and potential damage. When the turbine reaches either of the CW or CCW cable twist limits, the system must then brake to prevent further rotation and also trigger the yaw motor drive to return the system to its center position.

These dual requirements could have been accomplished using two separate devices— an encoder and a geared limit switch (such as from the previous example)—but this requires significant mechanical design and additional parts. As shown in Figure 7, a multifunctional position transducer solution was chosen—integrating both an encoder (angular position) and dual-channel geared limit switches (CW and CCW
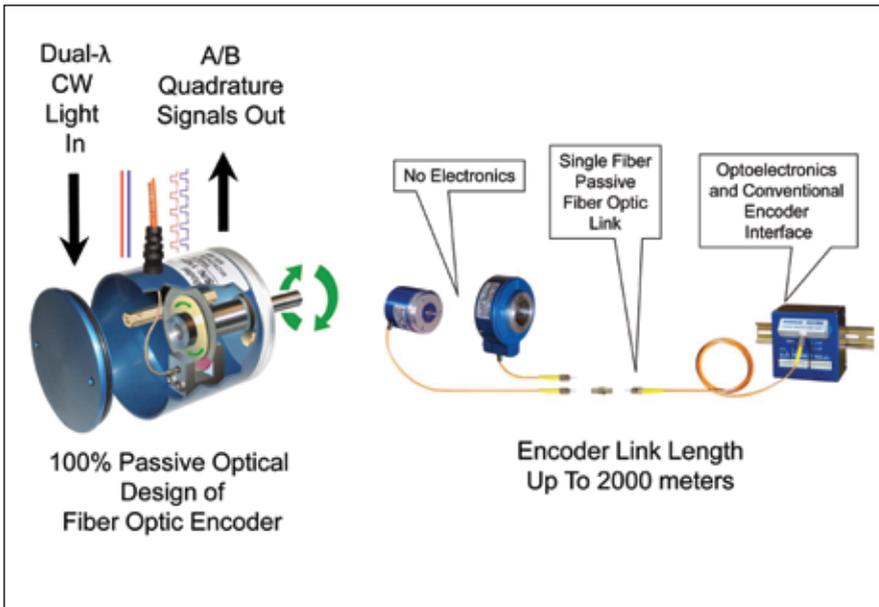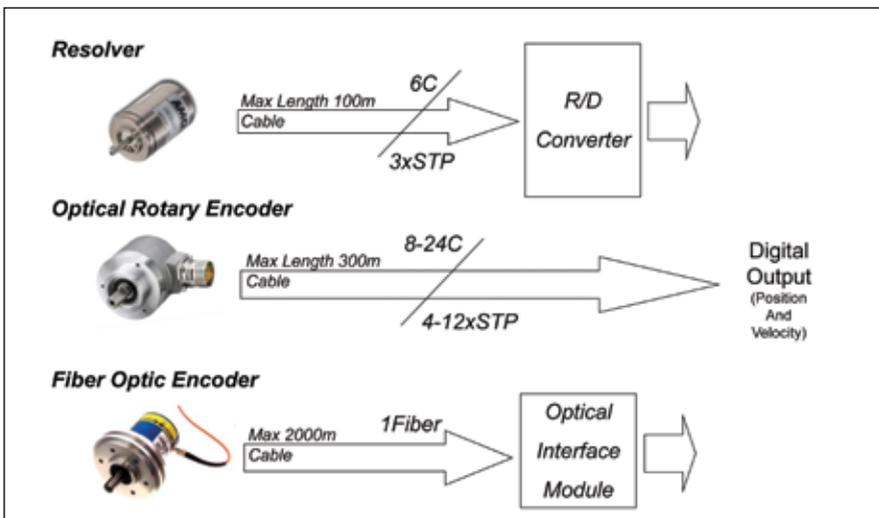
Figure 8—How a fiber optic rotary encoder works.

Dual-λ CW Light In

A/B Quadrature Signals Out

100% Passive Optical Design of Fiber Optic Encoder

No Electronics

Single Fiber Passive Fiber Optic Link

Optoelectronics and Conventional Encoder Interface

Encoder Link Length Up To 2000 meters

Figure 9—Comparison of resolver and encoder interface configurations and distance limitations.

Resolver

Max Length 100m Cable

6C

3xSTP

R/D Converter

Optical Rotary Encoder

Max Length 300m Cable

8-24C

4-12xSTP

Digital Output (Position And Velocity)

Fiber Optic Encoder

Max 2000m Cable

1Fiber

Optical Interface Module

Figure 10—Portland aerial tram uses fiber optic rotary encoders.

cable twist alarm set-points). This integrated unit mounts and couples directly to the main bull gear, simplifying mechanical design, minimizing parts, maximizing reliability and offering ease-of-installation and/or replacement.

Case #3—fiber optic rotary encoder for aerial cable car. Unlike the conventional optical rotary encoder, the *fiber optic rotary encoder* incorporates a unique, all-optical, totally passive design. As shown in Figure 8, the encoder uses a patented, wavelength division multiplexing technique that, essentially, shifts the optical rotary encoder's optoelectronics to a remote optoelectronics interface module and with all transmission occurring over a single fiber. In the fiber optic incremental encoder, two wavelengths are used, each corresponding to either the A or B quadrature signal.

The fiber optic rotary encoder is a deceptively simple design, consisting mainly of just two key components: a code wheel and the optical head. The fiber optic encoder's minimalist design makes it more robust and reliable than the complex, multi-component design of the mainstream optical or magnetic rotary encoder. The totally passive sensor offers EMI immunity, resistance to lightning, ground isolation and the ability to operate over extremely long distances (up to 2,000 m)—unmatched by any other type of position sensor. As drop-in substitutes for conventional encoders, the fiber optic encoder is also offered in both incremental and absolute models, as well as shafted and hollow-shaft configurations.

Aerial cable cars face conditions for which conventional optical rotary/magnetic encoders or resolvers were not suitable, due to exposure to lightning, EMI issues around large variable frequency drives (VFD), difficulty of providing power on high towers and the long-distance runs to remote sites and towers. A comparison of interface, distance and cabling characteristics of optical encoders, resolvers and fiber optic encoder is shown in Figure 9. In the case of the aerial cable cars, the fiber optic encoder best addresses the requirements and, in addition, offers the simplest installation solution (i.e., no remote power required or complex multi-conductor cable runs).

Type	Geared Limit Switch	Resolver	Opitical Rotary Encoder	Magnetic Rotary Encoder	Fiber Optic Rotary Encoder
Classification	Electronmechanical	Electrical (requires remote R/D interface)	Optoelectronic	Megnetic/Electronic	All Optical
Years in Use	100+ years	50+ years	10+ years	5+ years	5 years
Multiple Suppliers?	Few	Few	Few	Few	Few
Active or Passive Sensors?	Passive	Semi-Active	Active	Active	Passive
Temperature Range	-40/+85 C	-55/+125 C	-20/+70 C (+100C)	-20/+70 C (+100C)	-60/+150 C(+150 C)
External Interface Required?	No	Yes	No	No	No
Discrete or Continuous Position?	Discrete	Continuous	Continuous	Continuous	Continuos
Sensitive to EMI?	No	Yes	Yes	Yes	No
Remote Sensor Power Required?	No	No	Yes	Yes	No
No. of Conductors Required?	2-3C per switch	6 wires (STP preferred)	8-12C for incremental encoders. SSI and other field bus interfaces. (STP preferred)	8-12C for incremental encoders, SSI and other field bus interfaces. (STP preferred)	1 fiber
Maximum Distance	100m	100m	300-500m (depending on type of output drivers and EMI environment)	300-500m (depending on type of output drivers and EMI environment)	2000m
Cost	Medium	Medium	Low-Medium for Incremental Encoders. Medium-High Cost for Absolute Encoders.	Low-Medium for Incremental Encoders. Medium-High Cost for Absolute Encoders.	High

Table 1—Summary of the advantages and disadvantages of the five major types of position feedback sensors discussed in this paper.

As shown in Figure 10, the Portland (OR) aerial tram is a recent project incorporating the fiber optic encoders. The encoders are used both for speed feedback for the VFD motor drives as well as for monitoring synchronization of the cable drive system at various points.

Comparison table of position sensors. The following table summarizes the advantages and disadvantages of the five major types of position feedback sensors discussed in this paper. In addition, every application typically dictates a preferred type of position sensor, depending upon whether it's a new installation (favors latest technology), an upgrade/retrofit (favors existing or mature technology, usually not the latest) or repair (favors existing technology).