Synchro and Resolver

White Paper

High-Reliability Position Control for Rugged Applications

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Introduction

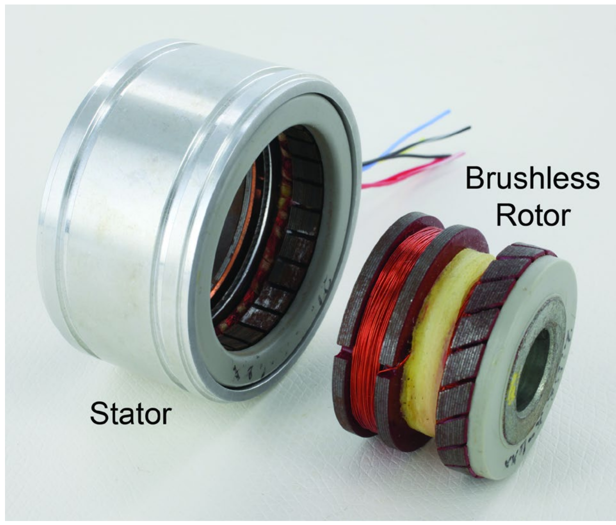

Figure 1. Resolver Mechanical Components

Synchro systems were first used in the control systems of the Panama Canal to transmit lock gate and valve stem positions, along with water levels to the control desks. From this, Navy designers realized the potential for position information to be used on-board naval ships. The original name for the sensor was Selsyn which was actually a brand name. This was later re-named synchro as a generic sensor name. Early naval applications included gun positioning of fire control systems first developed back in the 1920's. A synchro would transmit present gun position to the fire control system which would then transmit the desired position back to the gunner. Early position systems were simply moving indicator dials. As technology progressed into the 1930's methods were derived to enhance power thus rather than just moving a simple dial for position the actual guns and turrets could be moved directly.

Another naval application is the gyro compass. This large and heavy master gyro compass is located deep within a ship. The bridge needs the gyro compass information for navigation and combat systems. Transmitting the compass information via gears and shafts is impractical over long distances and curves, thus a transmitting synchro is used on the master gyro compass. The basics of the system are simple. The transmitting synchro has a rotor and stator. The rotor would be coupled to the gyro compass. The stator output would be sent to the receiving synchro stator. The receiving synchro rotor would be connected to a repeater compass on the bridge. As the gyro compass moves the transmitting rotor, a proportional change in current occurs in the transmitting stator which is sent to the receiving synchro stator. This causes the receiving synchro rotor to follow the position of the gyro compass, which is transferred to the bridge repeater compass.

Resolvers were created as a lower cost synchro where position is needed, but current drive is not required to move a shaft. Resolver signals provide information about the angular position of a shaft in the form of relative amplitudes of a carrier wave. All rotor and stator signals, input and output, are at the same frequency; all carrier signals are sine waves, in phase with all others in the system. To differentiate between time-phase angle and shaft-position angles, the latter are referred to as "spatial-phase" angles.

A 4-wire set of resolver signals, corresponding to the spatial phase angle, measured at terminals S1 and S3 (differential sine signals), and terminals S2 and S4 (differential cosine signals), would be represented mathematically as:

$$Vx = Kx \sin\theta \sin(\omega t + \alpha x)$$

$$Vy = Ky \cos\theta \sin(\omega t + \alpha y)$$

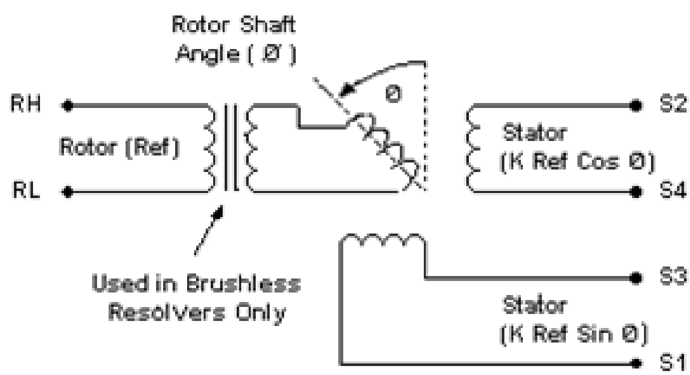

Figure 2. Resolver

Where:

Kx and Ky are ideally equal transfer function constants of the resolver; αx and αy are time-phase shifts (ideally zero); and $\omega = 2\pi f$, where f is the excitation frequency.

Thus, for any static spatial angle θ, the outputs of a resolver are sine waves with constant amplitude at the carrier frequency. The ratio of the amplitudes of signals in resolver format is:

$$Vx / Vy = \sin\theta / \cos\theta = \tan\theta \text{ and, } \theta = \arctan(Vx / Vy)$$

This ratio is independent of the frequency and amplitude of the reference excitation. The two main methods of Resolver-to-Digital conversion (i.e. tracking and successive approximation) are both ratio-metric conversion techniques. The angular error signal generated to null the loop is dependent only upon the ratio of the sine and cosine signals, and not their absolute electrical value. Therefore, as long as any voltage drops along the lines from the resolver to the converter are proportional, they will not affect the accuracy.

Another advantage of ratio-metric conversion is that the overall signal and reference waveform shape does not need to be a perfect sine wave. The Resolver-to-Digital converter can be operated with nearly a square wave or triangular wave provided the resolver magnetics do not stress as the waveform approaches DC levels as in the square wave.

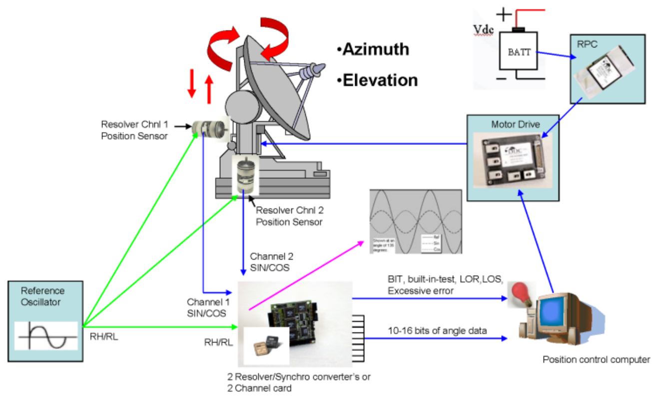

Figure 3. Example of Resolvers used for 2 Axis Antenna Control

Because the ratio-metric conversion technique cancels out modest frequency and voltage variations, low cost oscillators without tight frequency or voltage stability may be used. Modest frequency and voltage variations will not contribute to accuracy error. This leads to a wider range of oscillator choices that do not require high stability when used with a ratio-metric converter. Frequency, voltage, distortion and temperature variations continue to yield accurate results.

However, for customers using an oscillator with non-ratio-metric conversion techniques, this would be an issue of concern, and a very stable oscillator under all conditions should be used. As the amplitude changes, so does the bandwidth of the converter. As the amplitude drops below approximately 15% of nominal, the converter's hysteresis will increase. However, as the amplitude increases, it must be kept below the maximum voltage range of the converter input. If exceeded, this will cause accuracy error and possibly jitter.

Basics of Resolver, Synchro, LVDT, RVDT, Hall and Encoder Sensors

Synchro and Resolver

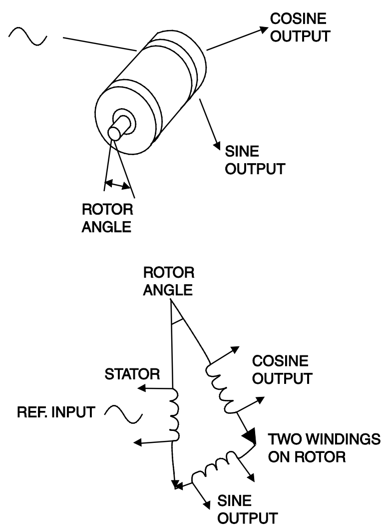

Figure 4. Synchro / Resolver

Table 1. Synchro / Resolver Characteristics	
Internals	Similar to a standard transformer with windings and laminations. No bearings needed.
Measurement	Used for 360° rotational position.
Uses	Navigation and fire control for ships, antenna control, aircraft applicationss such as radar, gimbals, fuel valves, landing gear, reverse thruster, cabin pressure. Ground vehicle applications including tank fire control, and industrial applications including CNC processing and robotics for joint position.

LVDT / RVDT

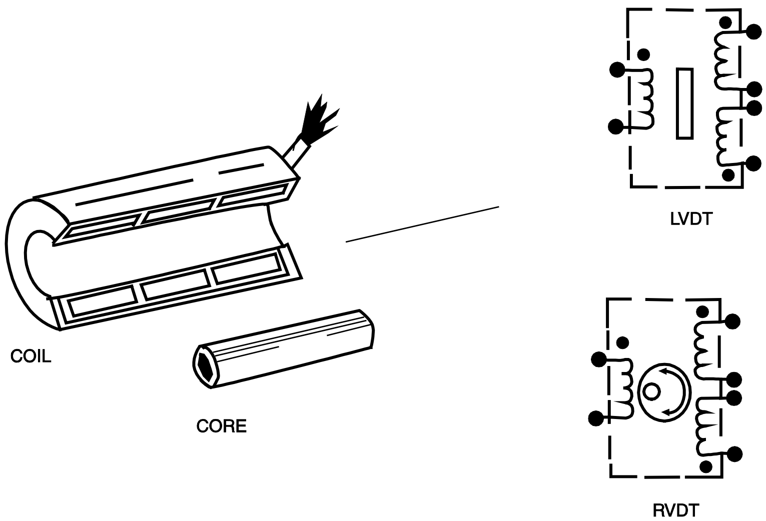

Figure 5. LVDT / RVDT

Table 2. LVDT / RVDT Characteristics	
Internals	Similar to a standard transformer with windings and laminations. No bearings needed.
Measurement	LVDT used for linear position, RVDT used for limited rotational position.
Uses	LVDT (Linear Variable Differential Transformer) sensors are used for manufacturing dimension inspection, weighing equipment, feedback for hydraulic cylinders, force control measurement, bore hole depth, height measurement for uniform manufacturing, and active control suspension. Examples of limited movement applications for RVDT (Rotational Variable Differential Transformer) sensors include aircraft wing flaps and throttle pedal position.

MR / Hall

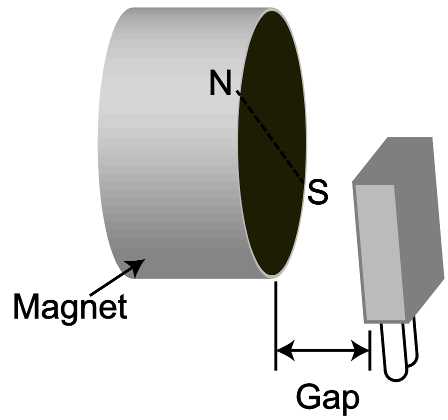

Figure 6. MR/Hall

Table 3. MR / Hall Characteristics	
Internals	Magnet and Integrated Circuit (IC). No bearings needed.
Measurement	Used for 360° rotational position or low end proximity sense.
Uses	Low cost applications where position does not need to be greater than 8-bit resolution.

Optical Encoder

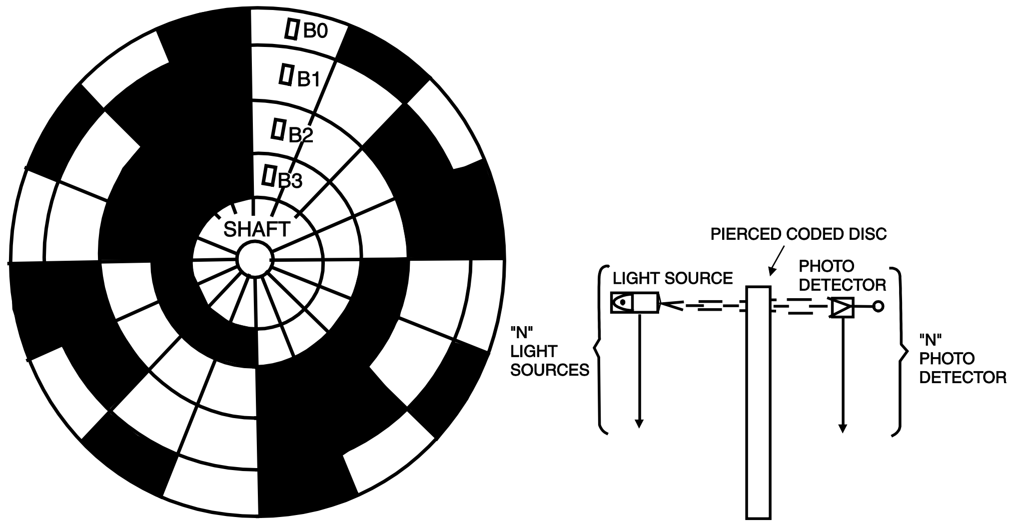

Figure 7. Optical Encoder

Table 4. Optical Encoder Characteristics	
Internals	Contains a disc with a dot pattern which represents counts / 360. Optics are used to sense a light source from the disc's hole pattern. As the disc rotates the light source makes – breaks – makes. Each make – break is used as a count for position. Position is output as a digital square wave via internal electronics. This device contains a shaft and bearings.
Measurement	Used for 360° rotational position.
Uses	Excellent choice when high resolution above 16-bit is required or lower cost is needed for 10 -12 bit resolution. Due to the internal optics and electronics, this device has limited use in harsh environments.

Selection criteria

Table 5. Selection Criteria

		Position Type	Tracking	Temp	Dust, Liquid on sensor	Resolution	Power	Accuracy	Size	MTBF
Sensor Type	Resolver and Synchro	360 Deg	~20,000 RPM, limited by the device used to process the output signal	Typical -55°C to 200°C widest range	No issue	16 bit, higher can be achieved with 2-speed mode, Resolution is limited by the device used to process the output signal.	Requires sine oscillator	Typical 2-3 arc Minutes, better can be achieved with 2-speed mode	Varies med to large	Hi
	LVDT	Linear	Typical up to 150 strokes per second	Typical -55°C to 200°C widest range	No issue	14 bit, Resolution is limited by the device used to process the output signal.	Requires sine oscillator	+/-0.005% of range	Varies med to large	Hi
	RVDT	0-30, 0-45, 0-60 Deg common	~20,000 RPM, limited by the device used to process the output signal	Typical -55°C to 200°C widest range	No issue	16 bit, Resolution is limited by the device used to process the output signal.	Requires sine oscillator	Typical ±0.25% to Best 0.01% Full Scale	Varies med to large	Hi
	MR and Hall	360 Deg and proximity	20,000 RPM	Typical -40°C to 125°C Limited by IC electronics	No issue	Typical 6-8 bit, better can be achieved using an RD converter	3.3 / 5v logic power	20 arc Minutes	Smallest	Med Due to internal electronics
	Encoder	360 Deg	15,000 rpm	Typical -10°C to 100°C, up to -40°C to 120°C Limited by internal components	Can impair optics, sealed cases are available using gaskets	Typical 16 bit, Best to 24 bit	3.3 / 5v logic power	Typical 20 arc seconds, Best to 3 arc seconds	Med	Lowest Due to internal shaft bearings & electronics

Examples of Common Applications

Table 6. Common Applications

Sensor Type		Military weapon fire control systems	Industrial where linear position is needed such as cutting and conveyer belt	Aircraft flight surfaces that have limited motion range such as flaps	Aircraft full motion range	Naval Ships, rudders, navigation, gyro	Robotics & factory automation	Antenna position	Open / close detection, low resolution position sense, water level detection with magnetic float
Sensor Type	Resolver and Synchro	Wide temp. range, ruggedness, MTBF			Wide temp. range, ruggedness, MTBF	Synchro for transmit and repeater, Wide temp. range and hi ruggedness, MTBF	Wide temp. range, ruggedness, MTBF	Wide temp. range, ruggedness, MTBF	
	LVDT	Wide temp. range, ruggedness, MTBF	Specially designed for best dynamics over limited linear range, wide temp. and hi ruggedness, MTBF						
	RVDT	Wide temp. range, ruggedness, MTBF		Specially designed for best dynamics over limited range, wide temp., ruggedness, MTBF		Specially designed for best dynamics over limited range, wide temp. and hi ruggedness, MTBF			
	MR and Hall		Lowest Cost solution						Lowest Cost solution
	Encoder		Hi resolution at lower cost				Hi resolution at lower cost	Hi resolution at lower cost	

Optical Encoders vs. Resolver Technology: Pros and Cons

Encoders

Encoders can give higher resolution beyond 16-bit, but they fall short under extreme environmental conditions of temperature, humidity or vibration. Higher resolution will provide better / more stable velocity at slower speed; i.e., "more data points". Also, for environments that are "dirty" with air contaminants, oil, grease or liquids the encoder must be sealed as these agents will impact the encoder's optical function. Due to the makeup of encoders including internal electronics, ("optic devices"), the range of environmental conditions that can be tolerated is limited.

Encoders can be incremental or absolute. Incremental "A quad B" encoders will lose position data when power is cycled off / on. The encoder must pass through the zero point to regain position. Also on initial start-up, the encoder must pass through the zero point to get position. Absolute encoders will retain position data when power is cycled off / on. Absolute encoders contain more electronics directly in the sensor and are capable of providing position data upon power up but will be further environmentally limited.

Encoders operate at low voltages, which may increase noise susceptibility. Spikes can occur on the low level signals of the light sensor / receiver giving spurious data counts, for radiation environments this can be a larger issue. Common temperature range is 0 to 100 degree C. Tolerable shock is 5 g's.

Resolvers

Resolvers do well to16-bit resolution and are rugged for all applications. For applications requiring greater than 16-bit resolution a method called 2-speed, which uses 2 resolvers geared together one spinning at 1x called the course resolver and another spinning at Nx called the fine resolver, can be implemented. The resolver's signals are sent into two resolver-to-digital converters where the data words are interpreted via software or by hardware using binary adders. Using a 2-speed method with a ratio of 1:30, 20 bit resolution is obtained. Ratios are available beyond 1:256 allowing many resolution choices. This method is viable when a rugged solution is required for high resolution even though the doubling of resolver parts required for 2-speed will make this a higher cost choice vs. a single encoder.

Resolvers have a transformer type makeup of wire, core, and package material, thus allowing the resolver to handle much more stringent environmental conditions by locating only the resolver at the operational end keeping the more sensitive digital converter located on the processing circuit board. High temperature, humidity, dirt, oil, grease and vibration present no issues for resolvers. Resolvers are absolute; they retain position data when power is cycled off / on. Unlike incremental encoders, there is no need to pass a zero point to gain position.

Resolvers can operate at low 2 volt and higher 90 volt ranges. The higher 90 volt range will provide better performance in EMI noisy environments and work best for long wire runs. (Low voltage will have greater loss over long wire runs). Common temperature range is -55 to 175 degrees C. Tolerable shock is 50 g's. Synchro's are still very popular on shipboard applications for transmit and repeating signals. For all other applications where only position indication is needed resolvers have become the modern choice as their dynamics, physical size and price offerings exceed synchro's.

Using Resolver for AquadB Emulation

For applications where an encoder has been designed in and the application ruggedness exceeds the encoder's capability a common solution is to replace the encoder with a resolver and use a converter device that can output AquadB signal "encoder emulation". By doing this the re-design effort from an encoder to a resolver is limited to a hardware only change. Since the converter will output a signal emulating an encoder there is no need for any system change to read the data.

Encoder vs. Resolver Summary

The choice between encoders and resolvers is application dependant. For rugged applications, a resolver will provide the best longevity. For non-rugged applications at slow speeds, encoders will provide higher resolution for better dynamic characteristics. In summary, resolvers should be considered the durable choice and encoders the higher resolution choice.

Aerospace Markets and the Need for Rugged Sensors

Figure 8. Rugged Sensors in Aerospace Markets

Sensors used in aerospace applications are exposed to many conditions that require rugged sensors that can survive harsh environments. Fuel & hydraulic fluid pumps which need precision valve control can be exposed to overspill of fluid from maintenance service which can come into contact with the position sensor. For sensors with optics any fluid coming into contact with the optics sense area are a concern for position errors. Resolvers are a better choice here as the magnetics of a resolver are not affected by fluids. Flight control surfaces such as slats, flaps, spoilers, ailerons, rudders, elevators and air-brakes are not only exposed to water and de-icer fluids, but also have temperature swings to consider. A sensor with internal electronics will have a narrow temperature range relative to a resolver sensor which has a mechanical makeup of copper windings and iron cores, thereby providing the widest possible temperature range.

As temperature drops toward the dew point, moisture can form on the sensor, as well as possibly frost. Both moisture and frost are an issue to optical sensors but will have no affect on magnetic sensors. Cabin pressure is controlled by means of a valve which requires precise position sense in order to adjust the cabin pressure accurately during altitude changes. A plane sitting in a cold or hot climate may exceed the operating temperature of a sensor with built-in electronics, in particular when these sensors aren't located in a climate controlled area of the aircraft. Conversely a resolver, which consists of windings and a core, will provide the widest temperature range for operating at these extremes. When looking at the many environmental factors encountered in aerospace applications, there is no question as to why resolvers continue to play a prominent role as the position sensor choice for aircraft.

Table 7. Examples of Usage in the Aerospace Market

Aerospace Applications	Used for	Important criteria
Slats, flaps, aileron, spoiler, actuators	Flight control	Environmental ruggedness, Temperature range, resolution, MTBF
Angle, compass, altitude	Indicators	Accuracy, resolution, MTBF
Start, wind-milling, thrust reversers	Engine	Environmental ruggedness, Temperature range, velocity, resolution, MTBF
Fuel, various fluids	Valves	Environmental ruggedness, Temperature range, resolution, accuracy, MTBF
Cabin pressure valve	Pressure control for altitude	Temperature range, MTBF
FLIR, antenna, IR	Gimbal position	Environmental ruggedness, Temperature range, resolution, accuracy, MTBF
Wheel and bay door position	Landing gear	Environmental ruggedness, Temperature range, resolution, MTBF
Motor control	Braking	Environmental ruggedness, Temperature range, resolution, MTBF

Industrial Markets and the Need for Rugged Sensors

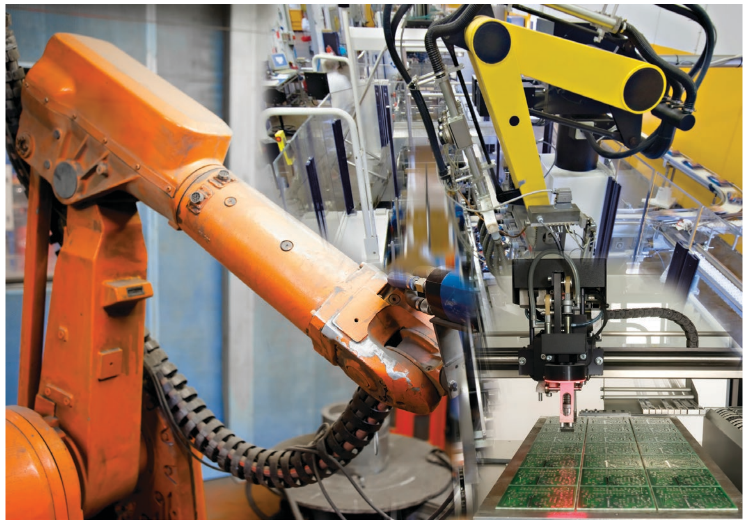

Figure 9. Rugged Sensors in Industrial Markets

Steel plants provide a good example of harsh environments where heat and air contamination particles will create abundant concerns when using an optical sensor. The high heat levels will reduce the longevity of a sensor with internal electronic components and the optics can be corrupted by any contamination that penetrates the sensor case. Sensor cases can be sealed using gaskets, but as with all sealing materials, the environmental stresses will age the seal over time. Eventually, all seals will fail, allowing penetration of the case. Resolver sensors do not need perfect seals as they are immune to internal contamination thereby providing the greatest immunity, reliability and MTBF for the harshest environments.

Consider an industrial application where repair of a failed sensor would mean not only down time, but also the added expense of a repair in a hard to reach place. The construction of optical encoders always requires a shaft and bearings to align the internal optics. As a result, the optical sensor encoder has a limited life not only due to the internal electronics but also due to the internal mechanical bearings and at some point in time all bearings will fail. Resolvers are available without bearings, as a bare rotor and stator where the rotor is placed over the moving shaft that is being followed for position and the stator is slipped over the rotor where only an air gap separates the rotor from the stator. The stator is then fastened to the case as the stator does not move. Using this method the resolver will not have bearings to wear out and thus will last the lifetime of the moving shaft assembly whose position is being tracked.

Figure 10. Example of Resovler-Shaft Coupling

Table 8. Examples of Usage in the Industrial Market		
Industrial application examples	**Used for**	**Important criteria**
Robotics control system	Position of joints	Temp. range, Resolution, MTBF
Laser cutter	Position of laser	Accuracy, MTBF
Cutting machines	Position of product for cut	Accuracy, MTBF
Nut driver / Runner	Servo motor controller	Temp. range, velocity, MTBF
Mine boring machines	Control angle of drill arm	Environmental ruggedness, Temp. range, MTBF
Nuclear power generation robotics	Control of fuel rod position	Environmental ruggedness, Temp. range, MTBF
Semiconductor production equipment	Direct drive motor control	Resolution, Accuracy, MTBF
Automobile production line	motor controller	Environmental ruggedness, Temp. range, resolution, MTBF
Wind power generator	angle control of blades	Temp. range, resolution, MTBF
Welding robot	Position of all arm joints	Accuracy, Temp. range, MTBF
Glass manufacturing: electric blowers, servo motor for glass bottle robotics	Speed and position	Velocity, Temp. range, MTBF
Komax wire processing machines	Speed control	Resolution, Accuracy, MTBF
Motor controllers	Speed	Velocity, Temp. range, MTBF
Oil Wells	Valve position control & down hole drill head position	Environmental ruggedness, Temp. range, MTBF
Textile	Position	Temp. range, Resolution, Accuracy, MTBF
Drilling	Speed control	Environmental ruggedness, Temp. range, MTBF
CNC machines	Position	Temp. range, Resolution, Accuracy, MTBF
All factory robotics	Robotic arm requires each joint to be positioned	Temp. range, Resolution, MTBF
Printing Press	Position: cutter and inkers, paper moving thru station	Temp. range, Resolution, Accuracy, MTBF
Automatic production and assembly lines (move product station to station)	Speed control and position of robotic work arms	Temp. range, Resolution, Accuracy, MTBF

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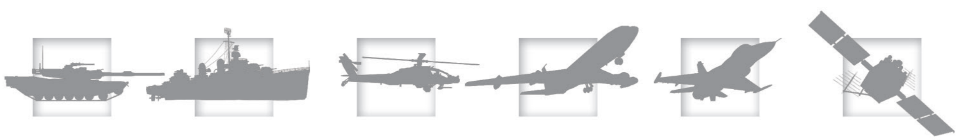

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