White Paper

Fast and simple measurement of position changes

Positioning systems in processing machines, precision measuring instruments, and handling robots require fast logging of position data and also quick recognition of any changes.
High resolution encoders and linear scales feed position data to the central control through an encoder interface. This interface must be selected so that it satisfies the timing requirements of the control unit. The vast number of available interfaces can also complicate the selection task as well as the implementation task for the designer.
Beside the great range of proprietary digital interfaces there are also open-source standards available, such as the SSI/BiSS interface for absolute position reading [1]. However, if a fast capture of changes in direction and/or of a very high position resolution is required, serial digital interfaces are limited in capacity.
As an alternative, there are of course the classic open-source encoder interfaces that transmit position as analog sine/cosine signals or position changes using incremental A/B signals as well.
The following article describes the requirements, alternatives, and possible solutions to this problem.

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1) Selecting the encoder interface

Utilizing a linear or rotary encoder in a system calls for an interface module at the Controller or PLC end (Figure 1). Many controller manufacturers provide a range of proprietary and open-source interfaces.

Analog

The classic non-proprietary interface transmits the position as analog data, either as a sine/cosine value which determines the absolute position on the receiver side by interpolation (sine-to-digital conversion), or as a current or voltage signal (e.g. 0–20 mA or 0–10 V). The latter is extremely common with simple position encoders. In safety applications analog differential sine/cosine transmission has the advantage that errors of the first order are detected [2] and are thus suitable for such applications.

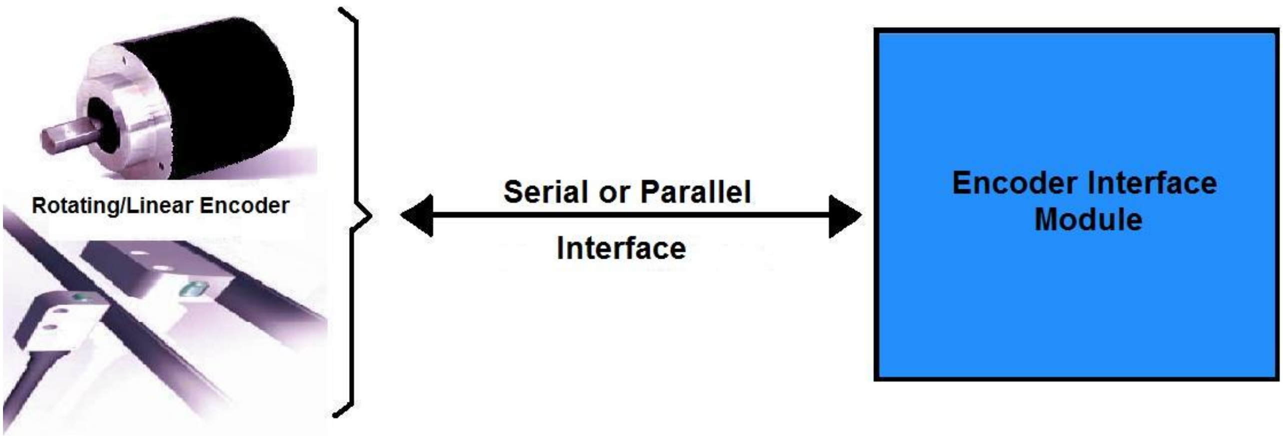

Figure 1: Encoder interface for controller or PLC

Digital Absolute

The fastest way of transmitting digital absolute position data is via a parallel interface. This interface is often implemented by a TTL-driver. However, the wiring effort for a parallel interface can be very high and as a result, this method is not very popular. Other methods increasing in popularity include standard non-proprietary field buses used in serial transmission, such as CANopen, Ethernet, and the open-source SSI/BiSS interface [1].

Digital Incremental

Another classic serial encoder interface provides incremental transmission of changes in position with two signals (A and B) shifted by 90°, also known as quadrature. In addition, a Z or index pulse provides the zero position for zero position detection. For the incremental interface, a change in direction is indicated by the phase shift of the A to the B or B to A signal.

Figure 2 shows the timing diagram of a change in direction close to the zero position. Here the given resolution for a rotary movement is one angular degree with a hysteresis of 1.4°. As shown, the A and B incremental signal phase shift allows detection of direction for up and down counting.

In this example, within one revolution, the A/B signals provide 360 edges (H → L or L → H). These edges must be evaluated for phase difference by a direction discriminator and directly activate an up/down counter. This then contains the absolute position of the encoder.

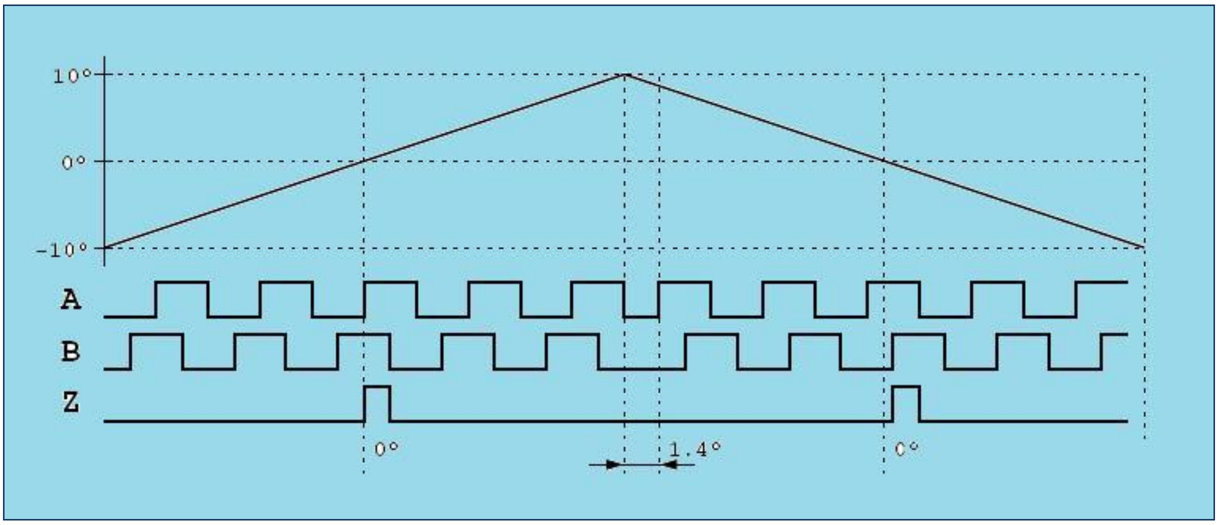

Figure 2: Timing diagram of the incremental encoder interface with A, B, and Z signals

The advantage of the incremental interface lies in its low cost and low wiring requirements. Typical configurations include TTL-driver, open collector, and line driver outputs. While TTL drive and open collector are lower cost solutions, line drivers offer many advantages. These include noise immunity via differential drive, driving of long cable runs, effective power dissipation, and fast serial transmission improvements. The benefits of differential pair transmission using special RS422 drivers allow much flexibility.

Changes in direction can also be quickly detected and speed determined simply by measuring the edge distance of two Z index pulses. An absolute position however is only available after a Z index pulse has been reached. With rotary movements this is achieved after at least one revolution. To this end, linear measuring systems require a reference or homing sequence prior to regular operation.

2) Fast control with current values

High precision requirements and fast movements generate very high clock frequencies which have to be processed by the interface module. Given this fast speed and positioning control, the achievable control cycle is dependent on the firmware algorithm and the delay times in the hardware.

By way of example, Figure 3 illustrates the components in a motor control system. In addition to the execution times in the firmware, the following times for the hardware must also be specifically taken into consideration:

a. Latency in the encoder: processing time with interpolation and output of the A/B signals

b. Transmission time between the encoder and the control unit/PLC

c. Readout time in the control unit/PLC encoder interface module.

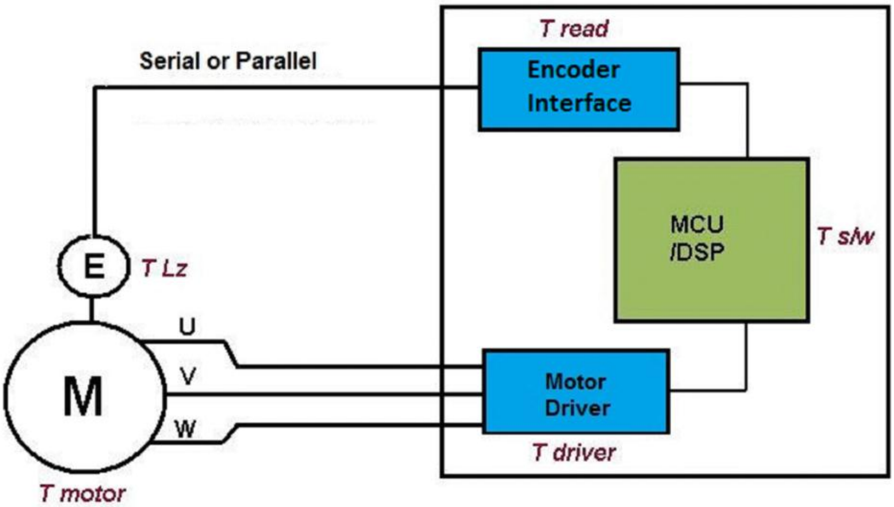

Figure 3: Timing components in a motor control loop

Encoder Latency

The latency (T_{Lz}) of the encoder is dependent on the bandwidth of the analog amplifier [2], the internal interpolation process, the resolution, and the encoder interface used.

Interpolator Latency

If sine/cosine interpolation on analog encoder signals is performed using an MCU/DSP-based system, the latency period can be as much as 200 µs or more. Special consideration should be taken when higher frequencies and resolutions are used, especially in conjunction with multi-axis control and redundant systems. In this case, latencies can result in position data that may not be current or synchronous. To combat this, a fast flash conversion based interpolator can be utilized (e.g. iC-NV). Given the parallel internal processing, a latency of less than 1 µs can be obtained.

Encoder Interface Latency

The data transmission time usually only plays an important role when utilizing serial encoder interfaces. For serial transmission, the readout time T_{read} of the position from the interface module to the MCU/DSP depends on the bit length and overall speed. For example, an SSI connection running at 10 MHz with a 32-bit format has a transmission time of 3.2 µs.

For incremental interfaces, the latency can usually be ignored given the real-time nature of encoder edges to movement of position. However, changes in direction will add some amount of latency depending on the hysteresis of the incremental signals (see Figure 2).

Processing Latency

Once position data has been read over the encoder interface, processing time ($T_{s/w}$) of the software algorithm adds to the system latency. This will vary between systems as processing time itself is largely determined by the architecture and processing capabilities of the MCU or DSP used.

Motor Latency

After the position data has been read and processed, the final latency lies within the motor drive itself. The motor is activated (T_{driver}) and then the reaction time (T_{Motor}) must be added to the overall system latency.

All of these delay times add to system latency and have a direct effect on the possible duration of the total control cycle. In turn, this also affects the productivity and accuracy of the overall machine's motor control system.

3) Merely counting is not enough!

The motor speed and encoder resolution determine the pulse repetition rate to be processed. However, other factors must be taken into consideration when selecting an encoder device.

Example Encoder Selection

As an example, for high speed applications, magnetic encoder systems such as the iC-MH permit motor speeds of up to 480,000 rpm at a resolution of 10 bits. These devices also provide the relevant motor commutation signals UVW as well [3].

Typical motor speeds are usually within a range of 500 to 15,000 rpm; however, resolutions of 12 bits or more are then often required. In this case, a speed of 120,000 rpm with12 bits of position data can be obtained with the iC-MH.

Given the iC-MH is a single-chip absolute encoder device, multiple interfaces are provided for the encoder interface. This includes both an SSI/BiSS serial transmission interface and an incremental interface. Focusing on the standard incremental signals, the A/B signals then have an edge repetition rate of 8 MHz. This allows a minimum distance between two A/B signals edges to be greater than 125 ns (see Figure 4a: Various electrical interpolator/encoder characteristics).

Parameter	iC-NV	iC-NQC	iC-MH/MH8	iC-TW9*
Resolution max.	6-Bit	13-Bit	12-Bit	16-Bit
Interpolation Faktor	x2 - x16 x1 - x10	x2 - 2048 x10 - x500	x1- x1024	x1 - x16384
Rotation RPM Maximum RPM	12.000.000 @ 6-Bit	9.600 @ 13-Bit 76.200 @ 10-Bit	120.000 @12-Bit 480.000 @10-Bit	7.500 @ 16-Bit
A/B-Frequency max.	3,2MHz	2,1MHz	8MHz	8 MHz
Min. Pulse Distance	30ns	120ns	125ns	31ns

*in preproduction

Figure 4a: Various electrical interpolator/encoder characteristics

Bits and Speed

Figure 4b gives the number of encoder pulses per revolution, dependent on the speed. At a resolution of 15 bits and 10,000 rpm a pulse repetition rate of almost 5.5 MHz is achieved. Standard encoders only obtain resolutions such as this at low speeds. With changes in direction the minimum edge distance is just as important and must be taken into account.

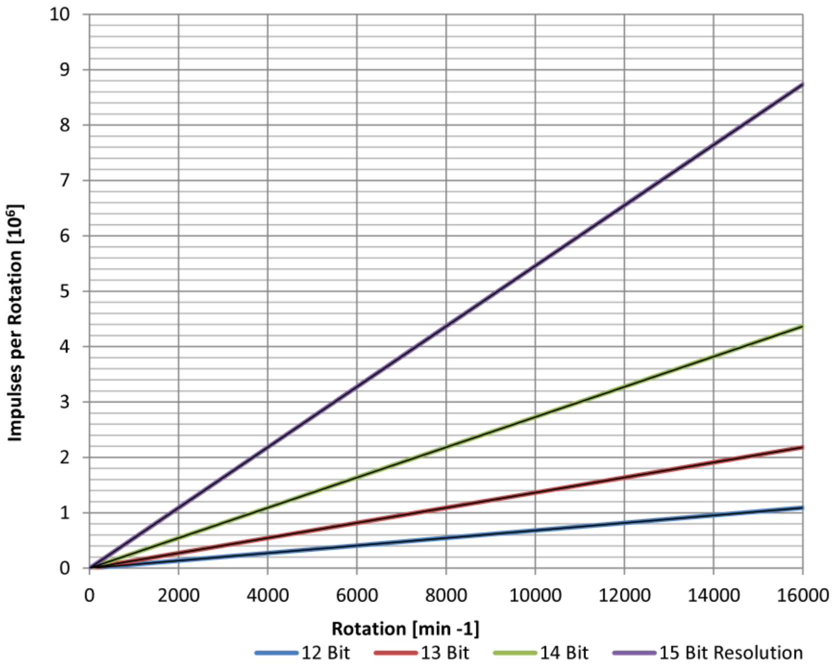

Figure 4b: Pulse rates depending on speed and resolution

Linear Motor Example

If linear motors are used, speeds of several meters per second are quite usual. With coreless linear motors, speeds of up to 7 m/s can even be obtained.

With linear scales, these provide a sine/cosine signal for a periodic division of 20 µm. By utilizing a downstream interpolator with a resolution factor of 16, such as the iC-NQC, a 1.3 µm step can be achieved. At a linear speed of 2 m/s this results in a pulse repetition rate of 1.6 MHz.

Besides the pulse repetition rate and the minimum edge distance of the A/B signals, the following must also be observed during development:

- Synchronous storage of positions from several axes at time t_X
- Simple speed measurement
- Detection of disturbances/errors during A/B signal transmission
- Programmable counter lengths in order to cope with different accuracies
- Single-ended and differential evaluation of the A, B, and Z signals

4) Building a fast incremental interface

Incremental encoders can be connected up in several different ways. With very slow movements it is sufficient to evaluate the edges using an interrupt and the MCU firmware.
If an external direction discriminator is used, or one integrated inside the MCU, A/B frequencies of several kHz can be scanned by the microcontroller's integrated timer/counter peripheral. With industrial controllers/motor control systems, FPGAs are also often used in the construction of encoder interfaces. Depending on the processing architecture, some of these systems are limited and cannot process high encoder frequencies. However, new developments in embedded controllers and dedicated encoder coprocessors can be utilized by the designer to solve these types of design challenges.

One such encoder coprocessor device is the iC-MD. As shown in Figure 5, this device provides a complete incremental encoder interface with integrated differential RS422 line receivers. The iC-MD can be connected up to either an SPI interface or to an SSI/BiSS interface.

The integrated direction discriminator activates a synchronous up/down counter of programmable length. This enables up to three channels of up to 16 bits each to be configured, or two at 24 bits each, or one 32-bit, or one 48-bit counter.

A 24-bit reference counter counts the number of A/B edges between two zero pulses. Together with two 24-bit registers, it is used to evaluate distance-encoded reference marks. The accrued reference counter value can also be used to compute the speed or the acceleration in the controller or the local MCU/DSP.

At an encoder rate of 40 MHz, the maximum count frequency is sufficient to permit an edge distance of at least 25 ns. The position of the first 24-bit counter can be stored and read out through an external event at the touch probe pin (TP) or through iC-MD's SPI/BiSS interface.

In a controller with several axes, this function helps store all positions synchronously at time t_x and to diffuse time delays through sequential readout.

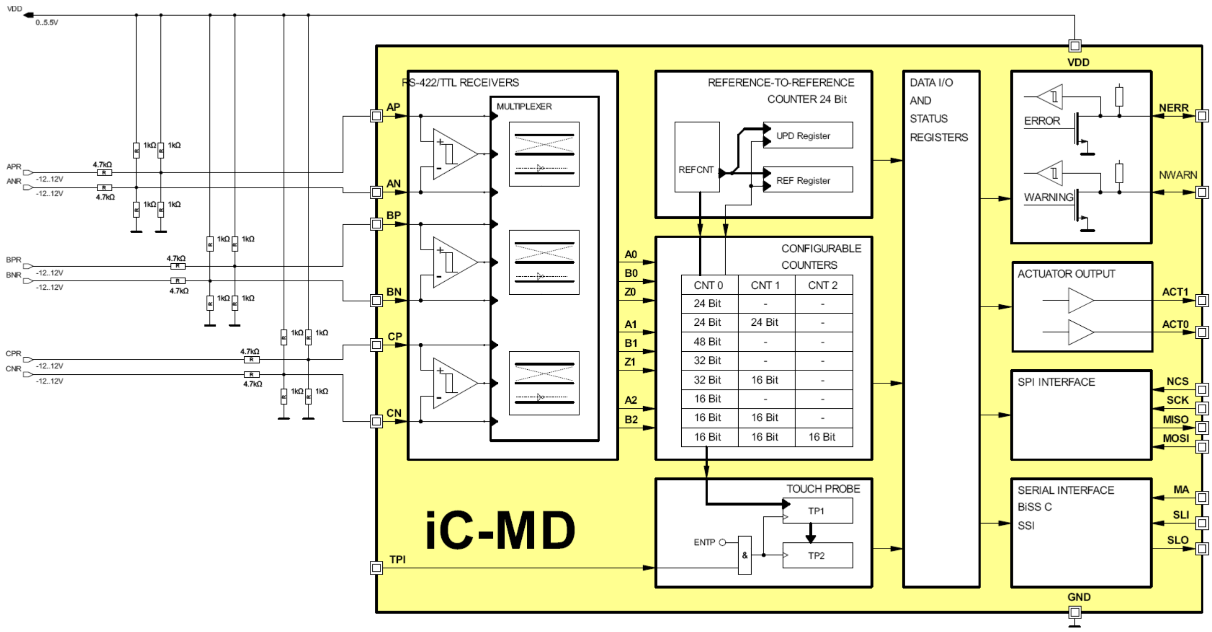

Figure 5: Three-channel incremental encoder interface with differential RS422 receivers

The A/B phase logic is also monitored by iC-MD and reported to the MCU/DSP with other errors, such as undervoltage, through an error output (NERR). Alarms, such as counter overflow or underflow, are indicated by iC-MD switching to low at output NWARN.

These outputs are bidirectional and are also stored by iC-MD as an external message and their status made available for readout through the SPI/BiSS interface. Two actuator outputs (ACT0/1) can be used by software and the MCU/DSP as signal outputs (for LED status displays, for instance) or as switching functions.

When considering the many design challenges of encoder interfacing beyond counting, the designer is faced with many challenges. By utilizing an encoder coprocessor, like the iC-MD, much functionality can be gained to an already existing MCU/DSP platform. By doing so, this reduces burden on the system and adds much capability and flexibility to the overall system design.

5) Summary

In the years to come, the demand for shorter machine throughput rates and more energy efficient positioning and drive systems will also prove to be a major challenge in the development of fast position sensors.

Targeted integration, as shown in the examples in this white paper, will help to meet these demands in a manner that is cost effective. Future iC developments are aiming for encoder clock rates of 100 MHz so that higher accuracies can be measured quickly and reliably.

6) Literature

[1] BiSS website: http://www.biss-interface.com/
[2] Flexible Sensor Signal Conditioning and Safe Transmission, Marko Hepp, SensorsMag, June 2010
[3] Measure angles on rotating systems with high resolution, Dr. David Lin, Automotive DesignLine, August 2007
[4] Using smart drivers to save energy for long transmission lines, Dr. David Lin, Industrial Control Design Line, July 2009

About iC-Haus

iC-Haus GmbH is one of the leading independent German manufacturers of standard iCs (ASSP) and customized ASiC semiconductor solutions. The company has been active in the design, production and sales of application-specific iCs for industrial, automotive and medical technology since 1984 and is represented worldwide. The iC-Haus cell libraries in CMOS, BCD and bipolar technologies are fully equipped to realize the design of sensor, laser/opto, and actuator iCs, Hall and encoder iCs and drivers and mixed-mode components. The iCs are assembled either in standard plastic packages or using chip-on-board technology to manufacture complete microsystems, multichip modules, and optoBGA™, the latter in conjunction with sensors.

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