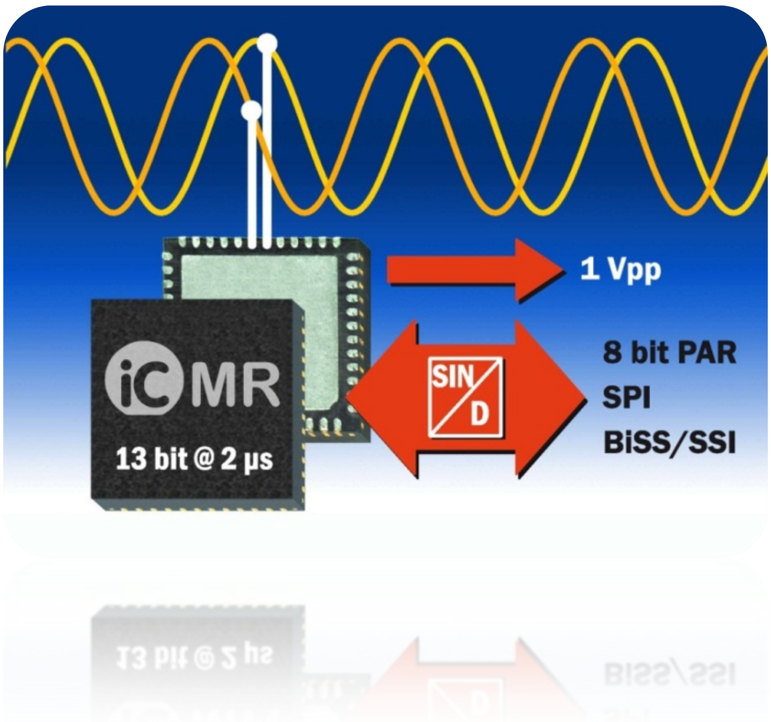
White Paper

High-Precision Sine/Cosine Interpolation

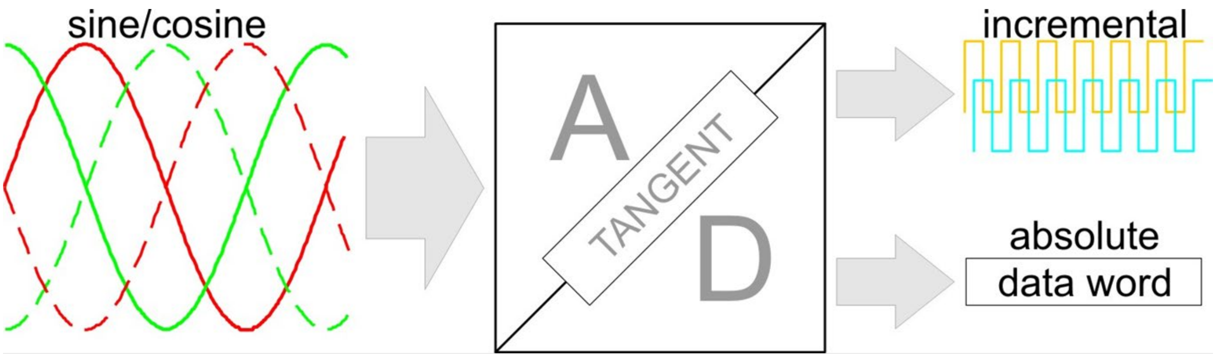
For speed control or positioning, drive controllers today demand high-resolution magnetic or optical position sensors which require special integrated circuits for sensor signal conditioning and sine/cosine-to-digital conversion.
This white paper describes the methods and challenges of the “interpolation” using sine/cosine-digital conversion (S/D conversion), it discusses sensor-related measuring errors as well as their compensation, and it illustrates the latest chip solutions and their selection.

Contents:



1. Methods of Sine/Cosine-to-Digital Conversion

High-precision magnetic and optical sensors [1] provide the angle or length information coded in a 90 degree shifted sine and cosine signal. The interpolation is responsible for the non-linear A/D conversion to transform sine/cosine signals into angle steps (see figure 1) that are displayed either incrementally as so-called quadrature signal, or as absolute data word which represents the sine signal's phase angle.



$$\varphi = \arctan\left(\frac{Vsin}{Vcos}\right)$$

Figure 1: Angle conversion via "interpolation"

The non-linear conversion function is usually the arc tangent, so that the phase angle PHI can directly be determined from the sine and cosine voltage.

Multiple A/D conversion concepts can be applied:

- a flash conversion, such as the one in iC-NV, which uses many individual comparators;

- a vector-tracking conversion, such as in iC-NQC and iC-MQF, in which only a few comparators control a counter upwards or downwards in order to first pick up, and then track the input angle;

- a SAR conversion (such as in iC-MR), which is similar in essence to the vector-tracking conversion, but which holds the input signal until the counter value has approached;

- as well as with a linear A/D converter (such as in iC-TW8), which digitalizes the sine and cosine signals separately, and subsequently calculates the angle.

Fully integrated magnetic and optical single-chip encoders, such as iC-MU or iC-LNB, use vector-tracking conversion to offer position data in real time [1, 2].

1.1 Flash Conversion

Figure 2 shows a flash conversion with many individual comparators, which each switch at different tangent function thresholds. At least one comparator is involved per bit of angle resolution, which implies a considerable hardware effort, and accordingly demands a lot of chip space – unless precision circuits are renounced. Therefore, this concept is only compatible with a relatively low resolution and only if the requirements for precision are not too high.

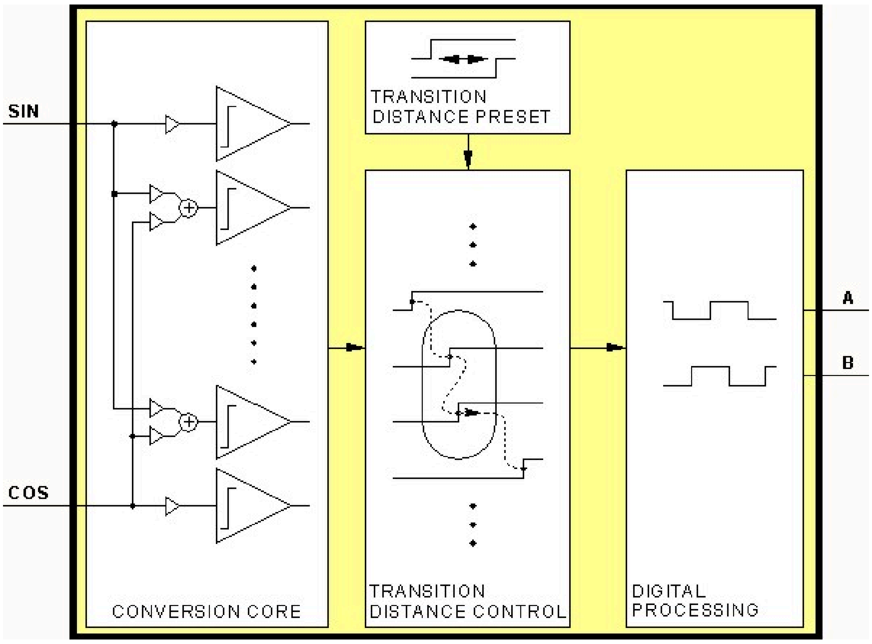


Figure 2: Flash Conversion

The fast conversion is advantageous: the comparators work parallel and switch almost simultaneously. Due to the development of switching spikes during settling, a patented edge distance control that creates equalization is applied.

Successive edges coming too close are shifted, so that an actually countable output signal is generated – the circuit functions as a filter, however, undisturbed input signals pass without a delay, i.e. this filter function shows no latency.

The flash conversion does not require sampling. Thus, the generated quadrature signals feature an “analog” jitter behavior as these are not aligned to any clock signal – which is ideal for speed controls. Typical applications which benefit from this type of converter are optical and magnetic motor encoders.

1.2 Vector-Tracking Conversion

The vector-tracking conversion is used for higher resolutions (see figure 3). It has one primary comparator which controls a counter upwards and downwards. The digital counter value feeds a D/A converter which produces an analog tangent signal. This tangent signal is mixed with the cosine, which then produces a sine signal – afterwards, sine is compared to sine.

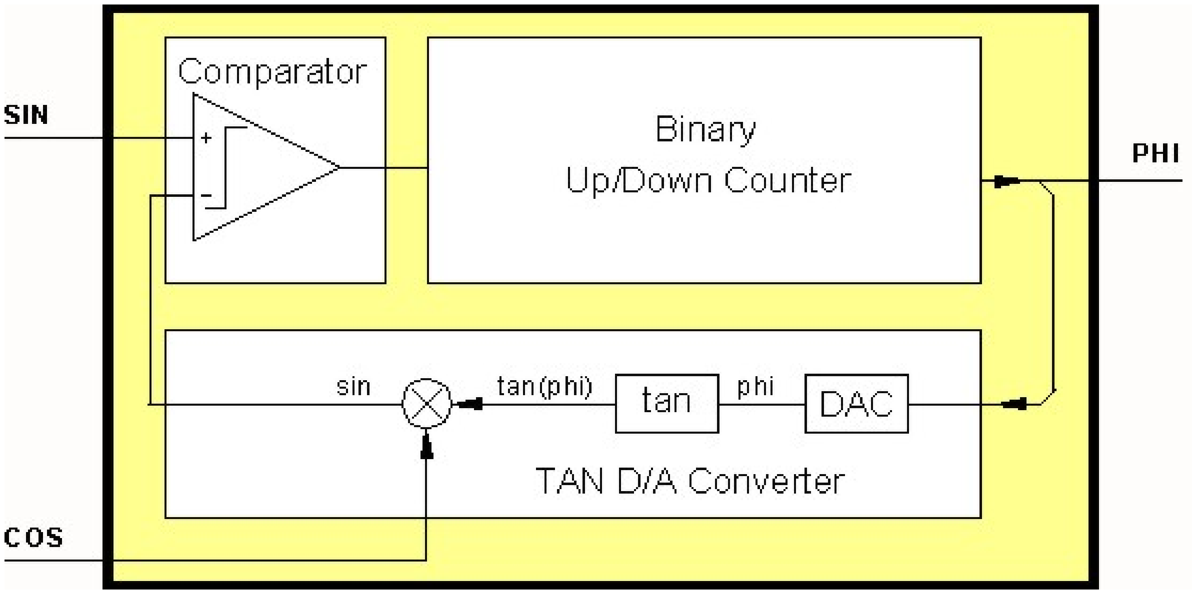


Figure 3: Vector-Tracking Conversion

When the system is settled, the counter contains the phase angle and tracks every input change step by step, or rather bit by bit – jumps are not possible. It is advantageous that this system as well functions virtually clock-free, and that it is activated only by an input change – the latency period is relatively short.

Since only one comparator is required, its design can be made for precision. An additional advantage regarding the accuracy is that a potential circuit offset error would affect all switching points the same way – comparable to a hysteresis. The tracking converter's incremental output signals jitter analog as well. A clock alignment is not visible until the adjustable limitation of the maximum tracking rate is reached, e.g. through a glitch at the input signals.

Due to its real-time characteristics as well as its high resolution, this type of converter is preferred for linear position measuring systems.

1.3 SAR Conversion with Sample-and-Hold Stage

For absolute measuring systems that do not have to output incremental signals, sampling converters as shown in figure 4 are suitable. The SAR converter works similarly to the vector-tracking converter, with the exception that the approximation register reaches the adjacent phase angle much faster because its steps can be larger and it does not have to track bit by bit.

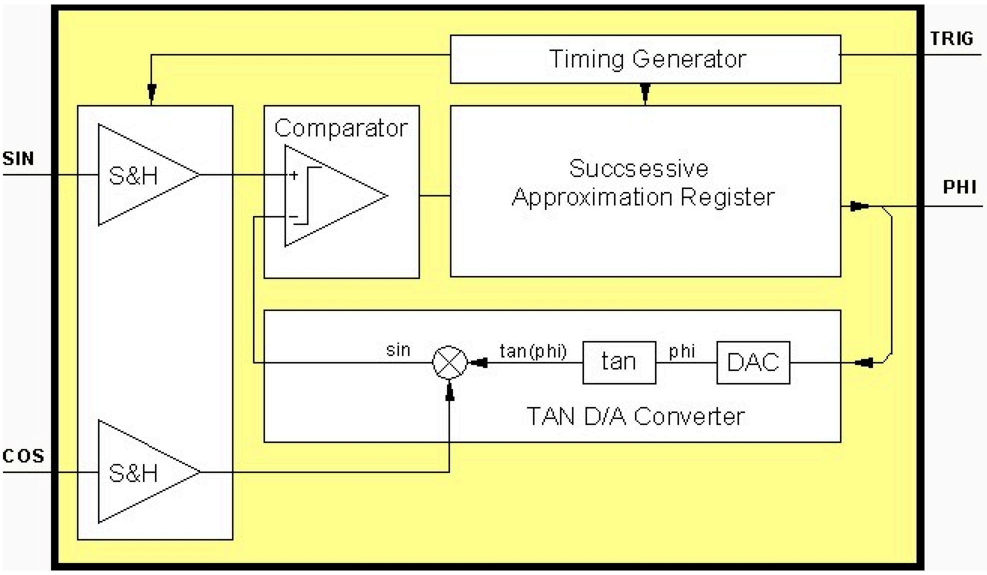


Figure 4: SAR Converter with Sample-and-Hold Stage

Triggered by the external data request, the input signals are frozen up through a sample-and-hold circuit. In this system, the analog settling time primarily determines how fast and with what precision the conversion can be executed.

This type of converter can usually be found in motor control systems and inverters which process analog encoder signals – or in position encoders, if very high angle resolutions are required.

1.4 Continuous Sampling A/D Conversion

The typical approach: iC-TW8 uses continuously operating linear A/D converters (figure 5) and calculates the phase angle afterwards. The advantage here is its digital signal processing: Signal errors can be deducted either one-time by pushing a button to ease initial calibration, or permanently by automatic functions to compensate sensor drift.

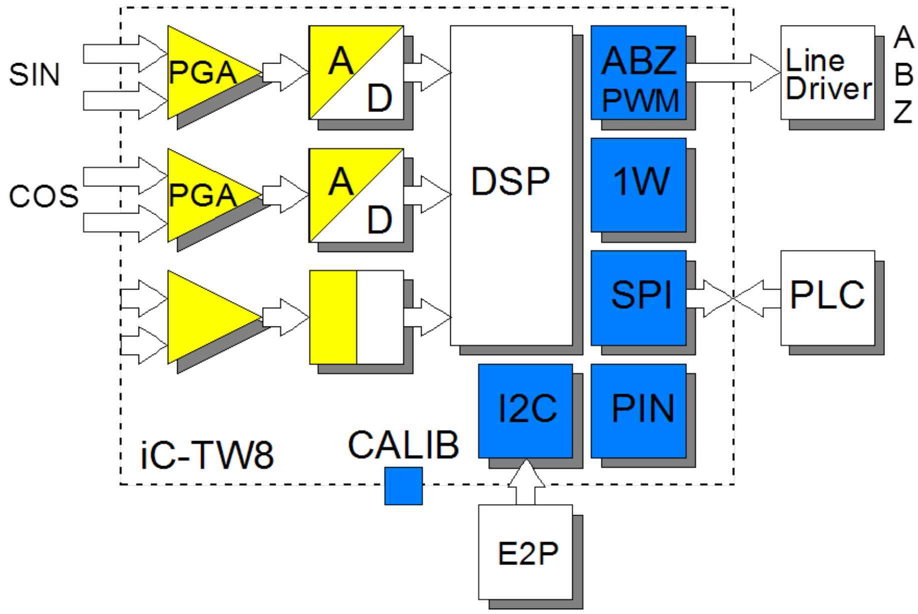


Figure 5: Sampling A/D Conversion

Signal filtering now makes it possible to reach resolutions which exceed the actually available A/D converter resolution. The synthetically produced incremental output signals show a perfect duty factor of 50 % and are nearly free of jitter. However, due to signal processing a constant latency time of a few microseconds is introduced, which may need to be considered in control systems.

Primary target applications are high-resolution linear length gauges, as well as rotary encoder systems which benefit from the supplied automatic signal correction.

1.5 Interpolation Devices in Comparison

Needless to say, the application determines which converter type is suitable: The tracking converters iC-NQC and iC-MQF persuade with real-time, the minimum latency of less than 250 ns is mainly determined by analog path runtimes.

With the sampling converters iC-MR and iC-TW8 the required settling time to the measuring value is decisive (see table 1) and can therefore limit the possible sampling rate. While iC-MR resolves the angle position with 13 bit within 2 µs, the continuously operating iC-TW8 requires 6 samples in total and 24 µs in order to renew its position data. On the other hand, if the speed is constant, iC-TW8 can reduce the existing latency to approximately 4 µs via an adjustable digital filter. As common for a resolver evaluation, the output position catches up the actual input angle – though in a significantly shorter time period.

Conversion Characteristics				
	iC-NQC	iC-MQF	iC-MR	iC-TW8
Principle	Vector-tracking SDC	Vector-tracking SDC	S&H SAR SDC	ΔΣ ADC + Cordic
Sampling Grid	14 ns [70 MHz]	50 ns [20 MHz]	2 µs [500 kHz]	4 µs [250 kHz]
Latency	< 250 ns	< 250 ns	2 µs	24 µs [4 µs]
Resolution	13 bit	12 bit	13 bit	16 bit
Accuracy per cycle typ.	10 bit 0.35° el.	11 bit 0.13° el.	12 bit 0.1° el.	12 bit 0.1° el.

Table 1: Conversion Characteristics

Besides the resolution, the accuracy must be considered as well, which is not only related to the A/D converter core's quality, but also to the dimensioning of the signal conditioning. Each D/A converter that takes corrective actions in the signaling path requires chip space, and consequently causes costs – an optimization task for the circuit designer. The comparison of the devices in table 2 shows that the converter iC-MQF provides a lower resolution than iC-NQC. However, it shows a higher precision due to a more finely graduated signal conditioning.

Safety-oriented encoder systems demand additional functions: the device iC-MR possesses special diagnostic functions, e.g. for signal and temperature monitoring, for memory checks, as well as for error simulation. For controller communication, one parallel interface as well as various serial interfaces are available. The configurable position data output via BiSS C can be carried out with life-cycle counting and an extended 16 bit CRC.

Operational Characteristics				
	iC-NQC	**iC-MQF**	**iC-MR**	**iC-TW8**
Supply	5 V	5 V	5 V	3.3 V, 5 V
Safety oriented			●	
Connectivity				
Sin/Cos	(test)	(test)	● 1 Vpp	–
Quadrature	●	● RS422	–	●
Serial	BiSS, SSI		BiSS, SSI, SPI	SPI
Parallel			8-bit	
EEPROM	I2C	I2C multi-m.	I2C	I2C
Multiturn			●	

Table 2: Operational Characteristics

2. Measuring Errors with Examples

The following example in figure 6 of a magnetic pole wheel scanning using MR sensors shows which measuring errors need to be considered, if necessary.

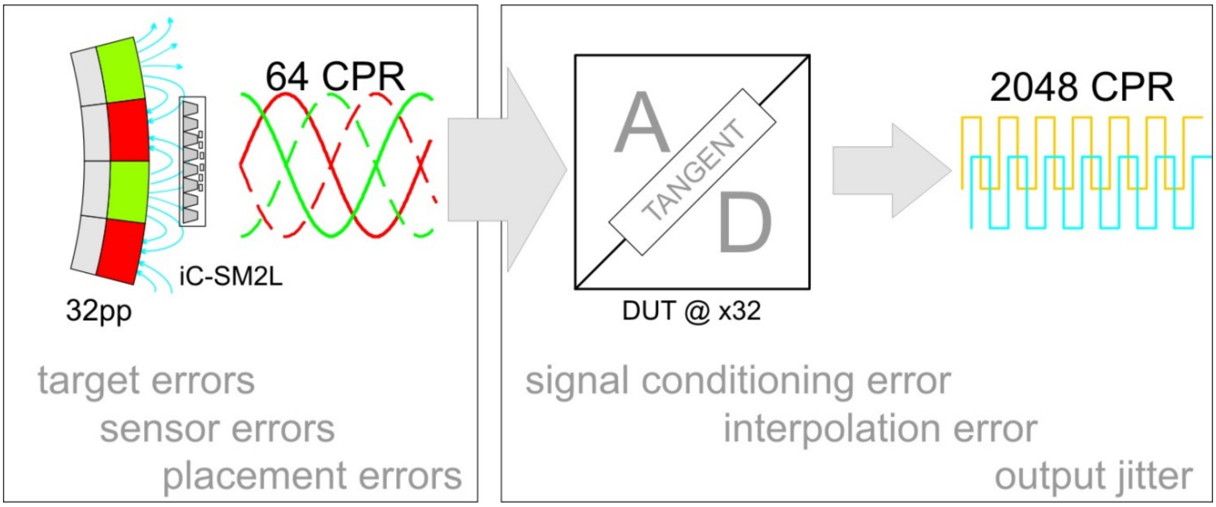


Figure 6: Application Example with Error Sources

Potential error sources can be:

- an imprecisely magnetized measuring target
- signal errors of the MR sensor regarding offset and amplitude
- sin/cos phase error through imprecise sensor alignment
- signal errors through false or insufficient conditioning
- measuring error through imprecise conversion

Without counteractions the interpolation result will be faulty and incremental output signals will stand out due to an excessively large jitter. The position jitter in consequence of mechanic angle alteration is certainly acceptable; jitter due to the measuring system, on the other hand, is not – unfortunately, a distinction and allocation is not possible.

Therefore, a precise knowledge of potential error sources is essential. The formula for angle calculation shows which signal errors need to be considered:

Waveform error

$$\varphi = \arctan \frac{\boxed{A_S} \cdot \boxed{F_{SIN}}(\varphi_S + \boxed{\varphi_{SERR}}) + \boxed{O_S}}{\boxed{A_C} \cdot \boxed{F_{COS}}(\varphi_C + \boxed{\varphi_{CERR}}) + \boxed{O_C}}$$

Amplitude error Offset error

Phase error

Formula: Angle Calculation via Arc Tangent Function

Relevant error sources are offset voltages, deviations from the ideal phase difference, differences between the sine and cosine amplitude, and possibly also distortions of the wave shape through harmonic contents. Thus, it would be important to know if all signal errors always need to be “conditioned” or if it is allowed to neglect.

Three case examples for estimating the required conditioning accuracy:

- magnetic, on-axis, 1 CPR: for 0.1° (12 bit) accuracy:
  signal errors < 0.2 % required (@ 200 Hz)
- magnetic, off-axis (32 pp), 64 CPR: for 0.1° (12 bit) accuracy:
  signal errors< 12.8 % required (@ 12 kHz)
- optical, off-axis, 2048 CPR: for 20” (16 bit) accuracy:
  signal errors < 22 % required (@ 400 kHz)

Example 1: If an angle accuracy of 0.1° is expected mechanically (12 bit/revolution) by an on-axis Hall sensor system which supplies only one sine period per revolution, it can be deduced that each signal error must be lower than 0.2 %.
This precise conditioning is certainly achievable, though the manual adjustment is very time-consuming and presents a possible challenge for the available measuring equipment. See tools at http://www.ichaus.de/tools.

Suitable devices are: iC-NQC, iC-TW8, iC-MR.

Example 2: While sampling a magnetic pole wheel via MR sensors the required interpolation depth, and technically also the requirements for signal precision are being reduced. Nonetheless, a more accurate conditioning will be preferred depending on how precisely the measuring target has been magnetized.
The input frequency rises with the number of poles – which is not a problem for vector-tracking converters due to the reduced interpolation factor.

Suitable devices are: iC-TW2, iC-MQ, iC-NQC, iC-TW8.

Example 3: When talking about an optical encoder system with e.g. 2048 sine periods per revolution, which should be resolved more finely, the requirements for the signal conditioning do not seem to be too high. However, the scale error generally already reaches the maximum permissible measuring error, so that an additional signal conditioning error cannot be tolerated (see table 3). Therefore, and because of the high input frequency, significantly higher demands can be made on the interpolation circuit. Sampling components such as iC-MR are required.

Calibrated Angle Accuracy		
Conditioning	Calibration LSB	Residual Angle Error
Sine Offset	0.2 % relative to Vpp	0.11° el.
Cosine Offset	0.2 % relative to Vpp	0.11° el.
Sin/Cos Amplitude Ratio	0.33 %	0.1° el.
Sin/Cos Phase	0.22°	0.11° el.
Harmonic Distortion	0.5% @ 5th.H.	0.29° el.

Table 3: Angle Error Depending On Calibration

2.1 Concepts for Signal Conditioning

In order to achieve a good interpolation result, sensor signals need to be conditioned [3]. Components iC-MQF and iC-MR apply an analog front end (AFE, see figure 7) for signal conditioning, which is adjusted via multiple DACs. In contrast, iC-TW8 applies a self-adjusting digital signal correction.

AFE for Signal Conditioning

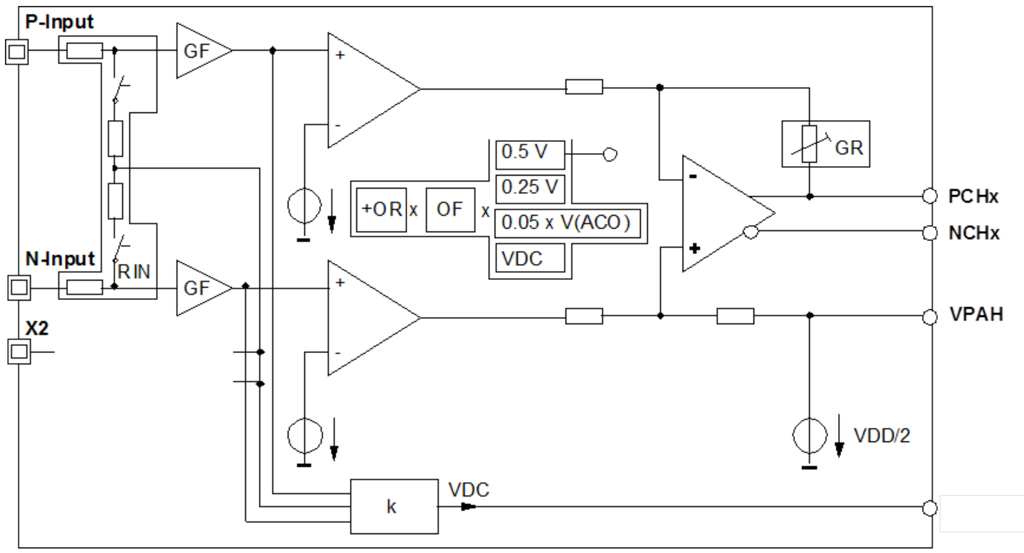


Figure 7: Analog Front End for Signal Conditioning

Precise instrumentation amplifiers offer a coarse amplification for signal adaption and balance signal differences through fine adjusters. A further aspect is the offset correction in the front end via D/A converters, which can track their correction signal-dependently. The front end can measure the DC component in the signal, as well as the sensor supply and use it for reference. Additionally, a current controller provides stable conditions e.g. by powering the MR bridge or the LED of optical systems. The advantage here is that, if adjusted at room temperature, the calibration accuracy is maintained even for temperature changes.

Key Features:

- integrated current/voltage conversion and voltage dividers
- offset-corrected instrumentation amplifiers
- separately adjustable coarse and fine gain
- sensor drift compensation through tracked offset references
- signal stabilization through regulated sensor supply (to sum value or Lissajous figure)

Digital Signal Correction

In the analog path, iC-TW8 only possesses coarse adjusters for gain and offset in order to get the input signals to a favorable range for A/D converters (see figure 8).

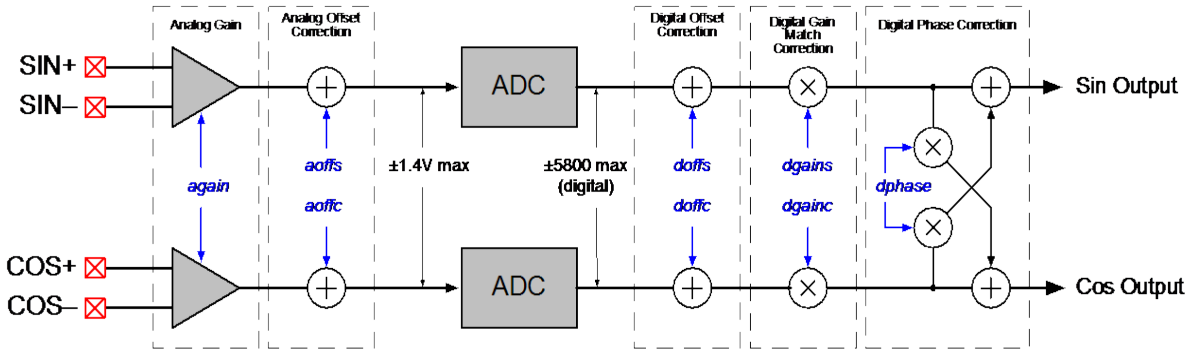


Figure 8: PGA Front End with A/D Conversion and Digital Signal Correction

Accordingly, merely digital, calculated signal corrections occur. An elaborate drift monitoring evaluates deviations from the factory calibration and can be configured for alarms. The angle position is calculated via CORDIC algorithm.

Key Features:

- adjustable coarse gain (6 to 45 dB, 3 dB/ step)
- adjustable analog offset correction (100 mV/ step)
- digital offset and offset drift correction (244 µV/step)
- digital compensation of gain mismatching (0.02 %/ step)
- digital phase correction (0.056°/ step)

Concept Strengths

Both concepts demonstrate strengths: After power on, corrections in the analog signal path settle already in standstill of the measurement system, in that the sensor power supply is adjusted to obtain the signal conditions at the time of calibration. There are no additional delay times in the signal path, fast interpolation results are possible. For initial factory calibration, measuring equipment is required which may need to be automated.

The digital correction uses the existing movement either initially to define its best suitable static adaption, or permanently for a dynamic drift compensation in the application. Measuring equipment for calibration is not necessary, recalibration in the field can either occur automatically or by pushing a button. This is beneficial for modular systems which are installed by the customer.

The following table 4 shows a cross-comparison of the devices with regard to the implemented correction possibilities.

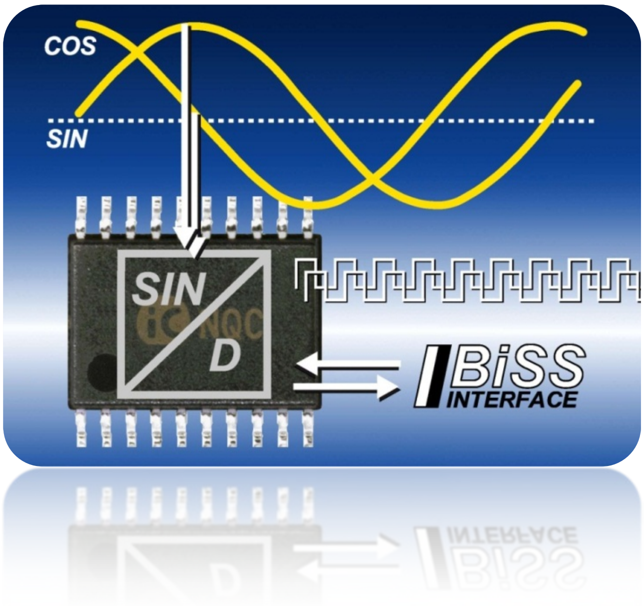
Signal Conditioning Characteristics				
	iC-NQC	**iC-MQF**	**iC-MR**	**iC-TW8**
Inputs	PGA	PGA zero-offs.	PGA zero-offs.	PGA
Inp. Frequ.	1(250) kHz	2 kHz	500 kHz	125 kHz
Signal Correction analog/digital				
Gain Ratio	● / –	● / –	● / –	– / ● auto
Offset	● (Vdd)	● (tracking)	● (tracking)	● / ● auto
Phase	●	●	●	– / ● auto
Drift Comp.	–	analog control output, digital (I2C)	analog control output	digital
Distortion				LUT
Signal Correction Accuracy				
El. Degree	0.35°	0.05°	0.05°	0.1°

Table 4: Cross-Comparison of Signal Conditioning

Devices Feature Overview

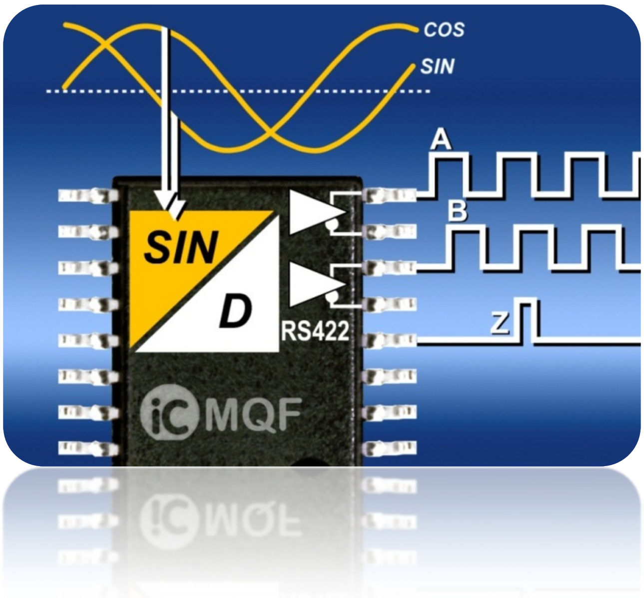
iC-NQC 13-bit Signal Conditioning Interpolator IC

- ✓ Real-time incremental
- ✓ BiSS absolute with period
- ✓ BiSS slave BP1, SSI



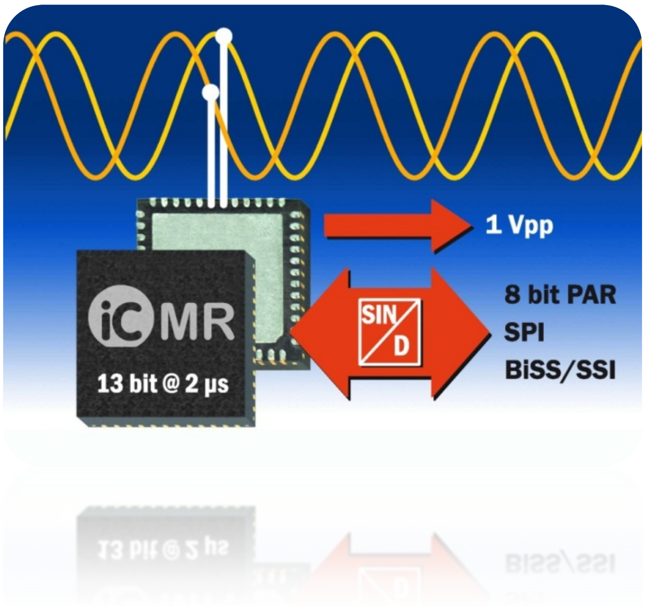
iC-MQF Programable 12-bit Sin/Cos Interpolator IC with RS422 Driver

- ✓ Real-time decimal incremental
- ✓ RS422 fail-safe
- ✓ Controlled sensor supply



iC-MR 13-bit S&H Sin/Cos Interpolator with Controller Interfaces

- ✓ BiSS or embedded
- ✓ Singleturn & multi-turn processing
- ✓ Safety monitoring features



Key Features:
Fast S&H interpolation: 2 µs, precision signal conditioning, source control output (ACO), 1 Vpp line driver output, parallel 8-bit µC interface, serial I/O (BiSS/SSI, SPI), I2C, 12-bit ADC (temper. sensing), safety features

iC-TW8 16-bit Sin/Cos Interpolator with Auto-Calibration

- ✓ Self-calibrating once/permanent
- ✓ Perfect incremental signals

Key Features:
250 ksps, 16-bit, constant latency (24 µs), lag retrieval to 4 µs (servo loop), binary/decimal x0.25 to x16384, post-AB divider [1/1 to 1/32], fin 125 kHz, A/B/Z 8 MHz, min. edge spacing t_{MTD} 31 ns , automatic offset, gain, phase, push-button calibration, distortion compensation via LUT, signal quality monitoring, setup by pins, I2C, SPI, 3.3V (15 mA), 5 V

3. Summary

As demonstrated through the different methods for S/D conversion, respectively for interpolation, multiple important criteria have to be considered in order to select the optimal solution. The current selection table [4] including the newest iC solutions can also be downloaded online.

4. Literature

[1] Encoder Technologies in Comparison: Magnetic vs. Optical, Elektronik 10/2012

[2] 18 Bit Absolut Encoder-IC, Elektronik Industrie 03/2012

[3] Easy Conditioning and Safe Transfer of Sensor Signals, Elektronik Industrie 4/2010

[4] Product Selector Interpolator IC

About iC-Haus

iC-Haus GmbH is a leading, independent German manufacturer of standard iCs (ASSP) and customized ASiC semiconductor solutions with worldwide representation. For more than 25 years the company has been active in the design, production, and sales of application-specific iCs for industrial, automotive, and medical applications.

The iC-Haus cell libraries in CMOS, bipolar, and BCD technologies are specifically suited to realize the design of sensor, laser/opto, and actuator ASiCs, amongst others. The iCs are assembled in standard plastic packages or using the iC-Haus chip-on-board technology to manufacture complete microsystems, multichip modules, and optoBGA/QFN in conjunction with sensors.

Further information is available at http://www.ichaus.com.