FPGA Based Sine-Cosine Encoder to Digital Converter using Delta-Sigma Technology
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Abstract
Since the very beginning of position feedback control, the industries wish has been to rapidly obtain a position signal with the highest possible precision, and this of course for a reasonable price. For accurate angle and position measurements optical encoders have shown to best meet these needs. An improved method for fast and high resolution synchronous evaluation of optical encoders with sine/cosine signals is presented that further enhances position measurement. Excellent disturbance and noise suppression and at the same time high signal frequencies are the key benefits. Analog circuitry is reduced to a minimum, thus all signal processing is performed digitally.

1. Introduction
In high precision motion applications the preferred feedback devices are optical encoders. While the resolution of pure square wave devices can only be increased to up to four times of the line count, sine-wave encoders provide two 90° phase shifted sine waves (sine and cosine signals) with one period per line that can be interpolated to theoretically any resolution. However, in reality high frequency noise and other adverse influences limit the potential of this technique. A high resolution position signal is usually desired though, in order to be able to provide the first or sometimes second derivative (velocity and acceleration) that are required by motion control systems.

Eliminating noise with simple low-pass filtering is not an option because the frequency of the signal also increases with velocity, depending on the application up to more than 250 kHz. Additionally, the filter would attenuate the signal and introduce a phase shift that reduces accuracy and limits system dynamics significantly [1].

A new method is presented that improves the quality and resolution of the position signal from sine-cosine encoders with a synchronous evaluation of the two analog signals. Noise and disturbance are suppressed effectively while not interfering with high signal frequencies.

1.1. Encoder Feedback
Most commonly, encoder feedback systems have optical or photoelectric sensors and compatible line structures. There are also encoders that work on magneto-resistive, inductive or even capacitive measurement principles. The wording in this publication is predominantly referring to rotary encoders, but all principles presented here are with minor adjustments also valid and applicable to linear encoder feedback systems.

Encoder Signals
The basic signals of every incremental encoder based feedback device are two 90° shifted square waves, which are generated by two 90° shifted scanners. They both detect the row of lines which is located on the rotating disc inside the encoder. To provide a unique reference point per revolution, an additional path with one so called “zero”-pulse is usually added (Fig. 2). The number of pulses per revolution is preconfigured by the manufacturer and cannot be changed. However it is a key parameter for the possible resolution of the position signal.

Fig. 1. BISS Sine-Cosine Rotary-Encoder by Hengstler [2]
The two shifted signals provide information about the position itself and the direction in which the axis is turning. As a first step to enhance the resolution of the rectangular signals provided by the scanners, not only the pulses themselves but also the timing of the rising and falling edges of the square waves are detected. This method provides a position interpolation (quadruple analysis) for a rotating motor, but it obviously does not improve position feedback capability for standstill and low speed.

To achieve a higher resolution, which necessary for accurate positioning and especially important for speed derivation, encoders are used that have sinusoidal or near sinusoidal output signals (Fig. 2). Now, theoretically any resolution can be reached by high resolution sampling of the two signals and calculating the arc tan of the quotient of the two signals.

Noise
In real systems, noise that is always present on analog feedback lines limits this technique. Ground loops and electromagnetic fields can be avoided to a certain extent, but thermal and EMI noise that is injected into the signals through the stray capacitances of the cables e.g. by the rotating parts of the machine will always be there. The two signals transmitted by sine cosine encoders are analog and the high resolution information is stored in their continuous actual values. This makes them prone to noise. The noise on the encoder lines is even harder to deal with since the frequency of the signals on them exceeds the system dynamics by far. The mechanical speed of the encoder is multiplied by the number of encoder lines to make up the frequency of the encoder feedback signal. Already for a rotary motor that runs at 6000 rpm with an encoder with 2048 lines, the frequency of the feedback signal exceeds 200 kHz. This factor makes filtering of noisy signals almost impossible, since not to lose any information, the cut-off frequency of a low pass filter would have to be even higher than that. The difficult task is to extract the position information of much lower bandwidth from the noisy encoder signals without losing precision or introducing time delays. It will be shown that ordinary low pass filtering is not enough. On the other hand, noisy feedback signals limit controller gains and ultimately system performance.

2. Conventional Encoder Feedback Signal Processing

The overview of conventional encoder feedback signal processing is shown in fig. 3.

2.1. Square wave reconstruction
One part of the position measurement consists of generating digital signals from the sine and cosine signals. This is done with Schmitt-triggers or threshold relays.

Sampling and Pulse Counting
At low speeds, where no or just one rising/falling edge is detected within a sample period, measuring the time between the edges and extrapolating from the last edge to the actual time gives a rough estimate of the position. Sub-line resolution provided by sine-cosine signals make this technique obsolete. At high speeds, counting of the pulses per sample period yields the coarse signal.
Every time an edge is detected, the new reference position is passed on to the high resolution part where the result of the sub-line analysis is added.

2.2. A/D Conversion

As mentioned above, in the second part of the position measurement, the analog sine and cosine signals are sampled and converted to digital signals. The sub-line resolution position value is derived by performing the arc tan of the quotient of the sine and the cosine signal value. Even though the arc tan calculation is using the quotient of the two filtered signals, it is necessary to utilize the entire input range of the A/D converters, to limit quantization errors and achieve the highest possible accuracy. Attenuated signals are therefore not desirable. However, filtering has to be done before sampling.

2.3. Signal and Noise

Inherently the signal frequency of encoders is a multiple of the mechanical frequency that they monitor. The multiplication factor is defined by the line count per revolution. For rotary encoders, a line count of 1024 or more is common. High speed encoders usually have lower line counts. While the frequency of the wanted signal can be relatively low (rarely more than 500 Hz), the signal frequency on the feedback lines is always much higher. And since the sub-line resolution information is contained in the analog signals of sine-cosine encoders, the information about the desired signal is part of the high frequency signals. The frequency range of the signals overlaps the high frequency range is where it becomes difficult to prevent noise (Fig. 5).

Low Pass Filtering

For both the threshold relays and the arc-tan calculation a noisy signal is deteriorating the position signal quality. Since the filter should be designed in a way that it suppresses the noise, but more importantly leaves the wanted signal unaffected, close attention should be paid to the attenuation and the phase shift of the low-pass filters. Already in standard applications encoder feedback signal frequencies can go up to more than 250 kHz. This means that any low pass filter has to take effect above this frequency in order avoid adverse effect on the quality of the wanted signal.

As explained above attenuation of the input signals in the range of the expected signal frequency should be avoided. If a maximum attenuation of 1 dB is accepted, the cut-off frequency for first order low-pass filters should be 1.97 times the signal frequency, or 491 kHz for 250 kHz signals.

The more harming effect of a low pass filter in terms of signal quality and system dynamics is the time delay or phase shift introduced especially into higher frequencies. The filter specified above would cause a phase shift of close to 27° for the maximum signal frequency of 250 kHz. This is definitely too much. If a maximum phase lag of 10° is permissible at 250 kHz, the appropriate first-order low-pass filter would have a cut-off frequency that is 5.67 times higher or 1.42 MHz [4].

A low-pass filter with such a high cut-off frequency is only filtering a small part of the noise. The bigger part of the noise stays with the signal with all the adverse effects connected (Fig. 5).

![Fig. 4. Conventional Encoder-Feedback and Observer](image1)

![Fig. 5. Frequency ranges for conventional encoder feedback processing.](image2)
Ideally, an adaptive low-pass-filter, that sets the cut-off frequency according to the mechanical frequency, would be the device of choice. But even if this was a feasible alternative at a passable necessary computation power, for high frequencies a great amount of noise would be still be unfiltered in the signals.

2.4. Observer
The observer shown in fig. 4 estimates the actual velocity (output signal) from the position of the machine monitored by the encoder and the acceleration imposed on it (input signals). From the estimated velocity, the observer calculates an estimated position. This value is compared to the actual value from the feedback system and the estimation error is used to adjust the estimated value of the velocity. The structure and its functionality are explained in [5].

3. Synchronous Encoder Feedback Signal Processing with Demodulator
The new approach to obtain a high resolution position signal with low noise and time delay (phase lag) at the same time consists of a “demodulator” and a tracking loop (Fig. 6), as described in [3]. The structure of the tracking loop is similar to that of the observer in the conventional structure that follows. This tracking loop also uses the estimation error to adjust the estimated position. But instead of comparing the estimated and the actual position to obtain the estimation error as this has been described e.g. for a resolver [5], the estimation error is derived from the “demodulated” sine and cosine signals from the encoder (Fig. 6).

3.1. Demodulation
The demodulation applies the following trigonometric addition theorem (1):
\[ \sin(A + B) = \sin(A)\cos(B) + \cos(A)\sin(B) \] (1)
to the estimation error \( \Delta \varphi = \varphi - \tilde{\varphi} \):
\[ \sin(\varphi - \tilde{\varphi}) = \sin(\varphi)\cos(\tilde{\varphi}) - \cos(\varphi)\sin(\tilde{\varphi}) \] (2)
where \( \varphi \) is the actual angle and \( \tilde{\varphi} \) the estimated angle.

For small \( |\Delta \varphi| \)'s, the sine of the estimation error can be further approximated to:
\[ \sin(\Delta \varphi) \approx \Delta \varphi \] (3)
leading to:
\[ \Delta \varphi = \sin(\varphi)\cos(\tilde{\varphi}) - \cos(\varphi)\sin(\tilde{\varphi}) \] (4)
A block diagram of this demodulator is shown in fig. 6.

Essentially the sine and cosine signals from the encoder are multiplied with the respective other signal from the tracking loop (“demodulated”) and at the same time the estimated and the actual position are compared. The result (the estimation error) is fed back into the tracking loop, which in return adjusts the estimated position.

3.2. Signal and Noise
The “demodulated” position-estimation error is proportional to the encoder acceleration. At constant speed the signal is zero. Due to this fact the estimation error carries only frequencies that range up to the dynamics of the mechanical system and in addition the noise that remains in higher frequencies. In the estimation error, the two frequency ranges do not overlap anymore.
which is illustrated in fig. 7. This allows to suppress much more of the noise in the “synchronous demodulated” signal. The wanted signal for this strategy is the position estimation error, which is of much lower frequency than the original analog signals.

Low Pass Filtering

The separation of the two parts of the signal permits simple low-pass filtering to suppress the noise.

It makes it also possible to completely remove the low-pass filters from the encoder signal paths and implement only one low-pass filter in the signal path of the position-estimation error as indicated by the red arrow in fig. 6. Filtering can now be done with a significantly lower cut-off frequency than before (e.g. 15 kHz), but still above the dynamic range of the controlled system. Such low cut-off frequencies would be impossible with the conventional method of encoder feedback processing. The low pass filtered error signal contains hardly any noise (Fig. 9). It is well suitable to be used as input for the tracking loop.

The characteristics of the noise from EMI and optoelectronic components are similar to that of thermal noise:

\[ v_n = \sqrt{4k_T R \Delta f} \]  \hspace{1cm} (5)

\[ \Rightarrow v_n \sim \sqrt{\Delta f} \] \hspace{1cm} (6)

By reducing the bandwidth \( \Delta f \) by a factor of 16 the rms-value of the noise voltage will be reduced by a factor of 4 (\( = \sqrt{16} \)). Therefore reducing the encoder cut-off frequency from 250 kHz to 15 kHz will reduce the rms-value of the noise voltage to \( \frac{1}{4} \). This corresponds to a resolution increase of 2 bit.

Experiences with the implementation of the new synchronous demodulation have shown that in most real systems the bandwidth can be reduced even more than only by a factor of 16.

3.3. Tracking Loop

The structure of the tracking loop is essentially the same as that of the observer in fig. 4, with the difference that there is no second input value like the acceleration. Its output is the estimated position value and consequently passed on to the velocity observer that remains in the same location of the control algorithm.

The bandwidth of the tracking loop should be selected high enough not to limit the dynamic range of the control loops.

4. Simulation and Measurements

The tracking loop shown in fig. 6 was simulated at a mechanical frequency of 500 Hz (30,000 rpm). The simulated encoder has 1024 lines per revolution. This setup leads to a signal frequency of 512 kHz.

Even at this high frequency and a large amount of added noise the tracking loop shows its good ability to reconstruct the correct position signal from the noisy signals (Fig. 8). In this simulation, the undistorted sine and cosine signals have a peak value of 1 \( \pm 1 \). The noise is of high frequency (capacitive coupling), with an average value of 0 and a deviation of 0.5.

The cut-off frequency of the low-pass filter for the tracking loop can be set so low that virtually all the noise is suppressed (Fig. 9).

In the simulated example shown in fig. 8 and fig. 9, the bandwidth of the tracking loop was set to 1 kHz, high enough for most applications. The cut-off frequency of the low-pass filter was set to 10 kHz. A low-pass filter with such a low frequency would be impossible to implement in the conventional approach. But here it does not affect the tracking loop at all in terms of phase lag and overall dynamics.
The lower part of fig. 8 shows the reconstructed position angle. It has no delay with respect to the real angle and no distortion at all.

The algorithm has been implemented in the industrial drive ServoStar 700™ by Kollmorgen (a Danaher Motion company) and proves to be very effective [6].

5. Conclusion

With this feedback signal processing strategy, much lower cut-off frequencies of noise filters are possible than ever before without affecting the signal dynamic bandwidth. Synchronous evaluation of both feedback signals in the demodulator makes it possible to specifically suppress noise while accurately reconstructing the actual position.

Especially at higher velocities, the presented algorithm provides a better signal quality of the position and velocity signals with increased resolution (additional 2 bit), less noise and considerably reduced dead times. Additionally, it can be implemented with less effort than known approaches.

Sigma-Delta modulator technology can be used to digitize as early as possible in the signal path of the encoder signals, thus eliminating all but the most necessary analog circuitry. While the analog portion is minimized, as much of the signal processing as possible is implemented in a standard FPGA. Programmable logic devices make the implementation flexible and help reducing costs. The digital components will continue to become cheaper with time, making the transition from analog to digital even more favorable.

References