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Different Types of Resolution Improvement Schemes in Optical Encoder

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Abstract: **This paper presents a comparison of the existing methods for improving the resolution of optical encoder. Optical encoders are mainly used for detecting the linear and angular speed or position of a system. From the existing system a new method for increasing resolution and accuracy of optical encoder is proposed. The simulation and experimental result are left for future work.**

Keywords: **Optical encoder, resolution improvement, interpolation, extrapolation, timestamp.**

I. Introduction

Optical encoders[1] are mainly used for detecting linear and angular position or speed in a system. Resolution of the optical encoder is very important where high precision of speed or position measurement is required. There are many methods for resolution improvement of optical encoder like Code composition technique by Nobumi Hagiwara and Yoshihisa Suzuki in 1992[2], High resolution position information from sinusoidal encoder by S.J Burke, J.F. Moynihan & K. Unterkofler [3], New interpolation method for quadrature encoder signals by K. K. Tan, Huixing X. Zhou, and Tong Heng Lee[4], Kalman Filter Calibration Method For Analog Quadrature Position Encoders by Steven C. Venema[5] . Martin stabler of Texas instruments [6] proposed a method which uses a sin/cosine interpolation technique to improve the resolution of optical encoder. In this method he used a high resolution algorithm for the interpolation process. For that he used a quadrature encoder which will give four counts for single cycle. The quadrature output channels A&B and the reference signal Z or R are processed, the output signal A&B are90^0 phase shifted. Rotation direction can be determined by detecting which one of the two quadrature encoded signals, A or B, is the leading sequence. Rotation speed can be determined by the frequency of the sinusoidal signals, A or B, with respect to the line count N of the encoder[7]. The angular position can be determined by knowing the incremental count or the line count and, when between two consecutive increments or lines, deriving the phase from the analog signals A and B. The reference mark signal R provides absolute position determination, if the angle at which the encoder is mounted is known. For the improvement of accuracy a method called timestamp is introduced by T.A.C. Verschuren (Eindhoven University of Technology) [8]. In this technique extraction of more accurate position and velocity estimations using time stamp is implemented. Time stamping is based on collecting time instants at which quadrature events take place. Polynomial fitting through previous collected time stamps and extrapolating this fit provides accurate position estimation. The time stamping concept is implemented using a low resolution encoder with TUeDACS/1 Micro Giant equipment]. It improves the accuracy of the position and velocity estimation, using only the encoder measurements. The Micro Giant has an encoder time stamp register, which stores counter values of the quadrature signal produced by the encoder and the time instant at which the corresponding transition has occurred. Time stamps from previous transitions can be used to achieve more accurate position estimation than the position measurement of the encoder by fitting a polynomial through these points. Furthermore, it is possible to prevent time stamps from entering the register. This can be done by skipping a number of transitions of the quadrature signal or by introducing a delay. In this way, more history of the position is taken into account as is done by storing all transitions. These additional options may lead to a better position and velocity estimation.

II. Resolution improvement algorithm using the sin/cosine interpolation

Incremental Position/Count: The incremental position can be determined by a timer that counts up when A is the leading sequence and counts down when B is the leading sequence. When digitized, both edges of A and B are counted, thus the incremental position ϕ_{incr} is given by

$$\phi_{incr} = (360^0/4N).incr + \phi_0$$

Where,
[incr] is the timer count or incremental count
N is the line count of the encoder
ϕ_0 is the zero position.

One incremental step is equivalent to a 90° (el.) phase shift of the signals, A and B.
The phase φ of the sinusoidal signals A and B can be used to interpolate the position between two consecutive line counts or four incremental steps, which are equivalent to each other. It can be calculated as

$$\varphi = \begin{cases} 90^\circ + \arctan\left(\frac{B}{A}\right), & A \geq 0 \\ 270^\circ + \arctan\left(\frac{B}{A}\right), & A < 0 \end{cases} \quad (2.1)$$

This has the advantage that the absolute amplitudes of A and B, which are a common function of the encoder's rotation speed and supply voltage. Since the arc tan-function is confusing, one has to chec k the sign of the sinusoidal signals A and B to identify the correct quadrant.

Interpolated High-Resolution Position

When the incremental count [incr] is matched to the phase φ according to
$Incr=0 \leftrightarrow 0^0 \leq \varphi < 90^0$, $incr=1 \leftrightarrow 90^0 \leq \varphi < 180^0$. etc., the high-resolution
Position/angle ϕ_a can then be derived as:

$$\Phi_a(incr, \varphi) = \frac{360^\circ}{N}\left((incr >> 2) + \frac{\varphi}{360^\circ}\right) + \Phi_{a0} \quad (2.2)$$

The sinusoidal signals A and B and the incremental count[incr] must be sampled simultaneously .
Practically, the digitized signals A digitized, B digitized, which edges are counted by the incremental counter, have a phase shift compared to the analog signals due to hysteresis and the propagation delay of the digitizing circuit. At the transition to the next quadrant, the incremental counter is not updated immediately because of the phase lag, e.g., as shown for the first quadrant in Figure 1.

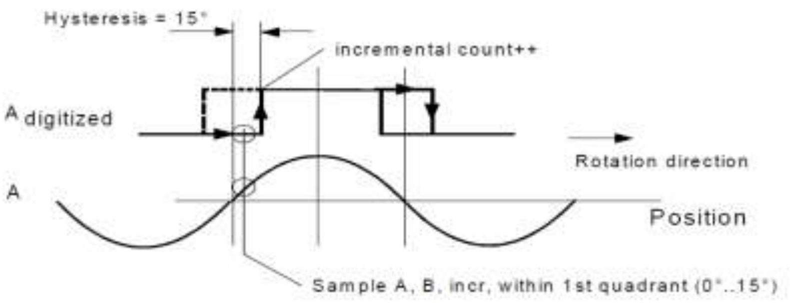

Fig. 1: Phase Shift of $A_{digitized}$ to A due to Hysteresis

Equation (2.2) can be applied as long as that phase shift is less than ±90° (el.),which is equivalent to a ±1 incremental count. Since only the phase information is used to identify the quadrant, there are only two exceptions (which may occur close to the transition to the next line) to consider when applying equation (2.2):

a) $0^\circ \leq \varphi < 90^\circ$ AND incr % 4 = 3.

Here the phase φ was obviously sampled before the incremental count was updated due to hysteresis and/or propagation delay. [incr] points to the wrong line count. In that case the incremental count [incr] is increased by one to compensate for that (known) error.

b) $270^\circ \leq \varphi < 360^\circ$ AND incr % 4 = 0.

In that case, the incremental count [incr] is decreased by one to compensate that (known) error.

Maximum Tracking Speed n_{max}

The maximum revolution speed at which the algorithm tracks the high resolution position depends on the following:

1 .Line count, N, of the encoder
2 .Hysteresis angle a of the digitizing circuit
3 .Propagation delay between the analog and the digitized signals
4 .Delay time between sampling the analog signals and capturing the incremental counter

$$n_{max}[rpm] = \frac{60}{N \cdot t_{delay}} \left(\frac{90^\circ - \alpha_{Hysteresis}}{360^\circ} \right)$$

III. Timestamp and extrapolation technique

Concept of time stamping: for the control of an electrical motor, information of its position and/or velocity is needed to obtain a good tracking performance. The common way to determine the position is to read out the encoder counter value at a certain sampling frequency of the controller. The number of encoder increments registered by the counter is a measure for the distance the motor has travelled. The measured signal is quantized because of the finite resolution of the encoder. Therefore, a quantization error on the position, with a maximum value of half an encoder step, is introduced. To obtain the angular velocity, the quantized position signal can be differentiated. However, the discontinuities in the position signal will result in spikes in the velocity signal.

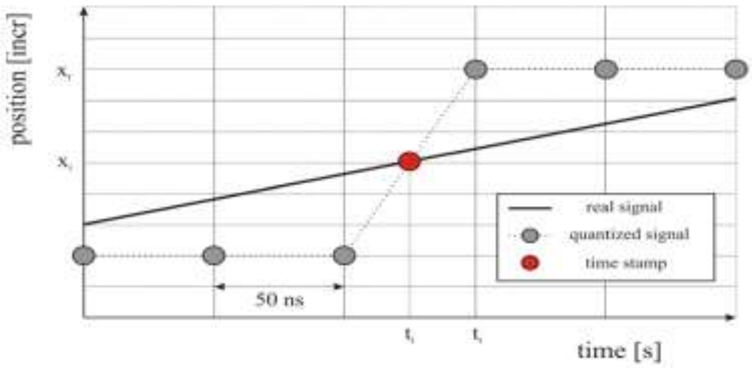

Figure 2: Concept of time stamping

Time stamping is also known as the event detection method. An event refers to the transition of one encoder increment to the next. At such step, the position x_i(see fig2) is exactly known, namely halfway the two encoder steps .It is possible to detect the time instant t_i at which such a quadrature event takes place. The combination (x_i, t_i) of a time instant t_i and the matching position xi is called a time stamp. The accuracy by which quadrature events can be detected is dependent on the clock frequency fc = 1/Tc. In this method the MicroGiant is used. In this device time stamps are evaluated with a resolution of 50 ns or with a frequency of 20 MHz The MicroGiant registers a quadrature event at time instant td, so the matching position would be x_d and the time stamp would be (x_d, t_d). Since, the resolution _ of the encoder is known the actual corresponding position equals xi = $x_d/4\alpha$. When encoder imperfections are neglected, the position therefore can be corrected to xi. The time stamp resolution of 50 ns is assumed small enough to neglect the difference between t_i and td. Finally, a time stamp consists of the pair (x_i, t_d). By using the time stamps of a certain amount of previous events, position estimation can be obtained by fitting a polynomial through these points. This fit can be extrapolated to have a very accurate prediction of the position at the time instant determined by the sampling frequency of the controller.

Extrapolation[9]: In the concept of time stamping, extrapolation plays a significant role. Extrapolation is the process of estimating beyond the original observation interval, the value of the variable on the basis of relationship with another variable, it is similar to interpolation which provides estimates between known observations. The order of polynomial fitting and the number of time stamps that are used to calculate the fit are important parameters. There are several methods to fit a polynomial through a discrete set of points. One of the most computationally convenient ways is the method of least squares which can be presented as solving a set of linear equations

$$\mathbf{A}\mathbf{x} = \mathbf{b},$$

$$\text{where } \mathbf{A} = \begin{bmatrix} 1 & \cdots & t_1^{m-1} & t_1^m \\ 1 & \cdots & t_2^{m-1} & t_2^m \\ 1 & \cdots & \cdots & \cdots \\ 1 & \cdots & t_n^{m-1} & t_n^m \end{bmatrix}, \mathbf{x} = \begin{bmatrix} c_0 \\ \cdots \\ c_{m-1} \\ c_m \end{bmatrix} \text{ and } \mathbf{b} = \begin{bmatrix} x_1 \\ x_2 \\ \cdots \\ x_n \end{bmatrix} \text{ with}$$

- n number of time stamps
- m order of the polynomial fit
- c_i polynomial coefficients, with i = 1, ...,m
- t_j time instants, with j = 0, ..., n

Assuming A is an m × n matrix with m > n, b is a n × 1 vector and x is a m × 1 vector.
The solution to this over determined system then can be formulated as follows:

$$x = (A^T A)^{-1} A^T b$$

To solve this equation for x and minimize the computational costs, LU decomposition[10] is used. The matrix A^TA is decomposed into a product of a lower triangular matrix, L, and an upper triangular matrix, U. The linear system $A^TAx = A^Tb$ can be written as $LUx = A^Tb$ and hence can be solved by first solving the lower triangular system $Ly = b$ by forward substitution, followed by the upper triangular system $Ux = y$ by back-substitution. Coefficients of the polynomial are known and an estimation of the position on a certain time instant can be determined with this polynomial $x_f = c_m t^m + c_{m-1} t^{m-1} + \cdots + c_0$.

IV. Comparision of above mentioned methods and proposing a new method from existing techniques

By analysing the previous researches on the resolution improvement techniques, one can understand that the optical resolution improvement by the optical encoders physical resolution is somewhat good but the track size of the encoder disc will increase by increasing the physical resolution and that result in the increased size of the encoder. so in some equipment's where the size is concerned, for example in satellites modules we have to reduce the size and weight. so in this type of situation we are increasing the resolution by without increasing the physical resolution and here we are using the electronic resolution improvement techniques for the desired modules or systems. When referring to sin/cosine interpolation technique by Martin stabler one can understand that the resolution is improved four fold to the physical resolution. So by analysing the algorithm he mentioned in that technique, is very much good for the resolution improvement. In this technique a high resolution algorithm was developed and implemented on a dsp controller. The computations of algorithm were very hard, so a look up table based computation technique is introduced for the easiness of calculations and the results are verified. By this technique the computation time and error is reduced. By using this algorithm the resolution is digitally increased by five finer bits.

By reviewing the timestamp technique proposed by T.A.C. Verschuren it is clear that the accuracy of optical encoder can be increased for the measurement of position or speed of a rotating system. In this technique he used a timestamp algorithm with an extrapolating technique for the improvement of the accuracy. A polynomial fitting method is also introduced for the calculation of speed or position, when the order of the polynomial fit is increased it is seemed that the algorithm fails for determining the exact position or speed. so the simulations for the different order of polynomial fit is carried out. A technique called skip and delay of time stamp is implemented for the improvement of the accuracy in the timestamp method. The simulation of skip and delay is also carried out, from that it is understood that when the skip or delay is increased the accuracy seems to be decreased. So by comparing both techniques mentioned above, both algorithms fail when considering low velocity profiles. So to increase the accuracy &resolution of optical encoder for detecting the exact position or speed a new approach is proposed, by combining the sin/cosine interpolation and time stamping algorithms. The combined algorithm can be implemented on a single dsp controller and also it will reduce the size and cost of the hard ware.

Conclusions

The different types of resolution improvement techniques are studied. From the different types of method two methods called sin/cosine interpolation and time stamping is considered. The selected methods were compared and simulated. From these methods a new method is proposed. The simulations and the experimental results of the new method are left for future work.

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