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Precise and robust position estimation for optical incremental encoders using a linearization technique

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ABSTRACT

In this paper, an amplitude-to-phase converter for optical incremental encoders is presented. The proposed converter is based on a linearization technique that coverts the sinusoidal signals into a nearly perfectly linear output signal, from which displacement can be determined precisely using a simple linear equation. The theoretical error of the converter is within $\pm 0.0196\,\mu m$ for an optical encoder with a period of $20\,\mu m$. Simulation results indicate that the proposed converter is significantly more robust to the signal imperfections than the commonly used arctangent algorithm. A signal pre-processing circuit is also developed to further reduce the positioning error caused by the signal phase-shift error. The proposed converter was successfully implemented with a Field Programmable Gate Array (FPGA), and applied to an optical encoder. The robustness and effectiveness of the converter have also been confirmed from experimental results.

1. Introduction

Optical encoders are indispensable in leading-edge technology manufacturing, such as ultra-precision machining equipment and semiconductor manufacturing equipment, where high-precision positioning is required. Optical encoders employ sinusoidal signals to represent position information. In order to determine the position from the amplitude of the sinusoidal signals, suitable amplitude-to-phase converter is required [1,2]. Usually, arctangent algorithm is applied to these two sinusoidal signals. This ratiometric technique has an obvious advantage that its output is insensitive to the amplitude fluctuation of the signals. Generally, the highly nonlinear arctangent function requires a look-up table for the computation of a phase [3–5]. The look-up table is constructed offline. It contains the information to map the measured signals to ideal signals, and interpolates the ideal signals into higher order sinusoids and converts those into pulses. In order to make the mapping from measured to ideal signals a reference encoder is needed. The main drawback of a look-up table is, if it is generated without a reference encoder, the disturbances in the setup will be put in the look-up table. This results in the encoder giving an inaccurate position [6]. What's more, making such a look-up table is time-consuming and would occupy more memory when high degree signal interpolation is applied.

To solve above issue, converters based upon linearization technique have been proposed by Benammar et al. These converters produce an output signal proportional to the displacement, which enables linear determination of the displacement with reasonable accuracy without look-up tables. The schemes, based on linearization of the difference between the absolute values of the sine and cosine signals [7] and the alternating pseudo-linear segments of the sine and cosine signals around zero crossings [8], were successfully implemented and verified.

In practical applications, the performance of the converters is always limited by the quality of the electrical signals generated by optical encoders. The signals are usually affected by a number of circumstances, mechanical, optical or electrical, etc. The imperfections in the electrical signals, such as amplitude imbalance, imperfect quadrature, zero-offset error, harmonic distortion and amplitude fluctuation, will introduce nonlinear errors [9–11]. Although several methods have been proposed to correct the signals in real-time [12–14], due to the requirement of the extraction of signal peak value, these methods do not work properly under situations, such as measuring a target moving with small step that less than a quarter pitch of the scale grating [15], where there would be no peaks appear in the signals. As an option, design of a converter, that is robust to the imperfections in encoder signals, may

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be a valid way to further improve the accuracy of optical encoders in practices.

Following the previous work [16], an amplitude-to-phase converter with improved robustness, incorporating a new linearization technique, is proposed in this paper. The converter enables precise and linear determination of the displacement from encoder signals. Due to the robustness of the proposed converter to signal imperfections, it would improve the accuracy and resolution of optical encoders. The overview of an exposed optical incremental encoder is addressed in Section 2. Operating principles and theory analysis of the proposed converter are described in Section 3. In Section 4, positioning error caused by non-ideal input signals is analyzed and a signal pre-processing circuit is developed to correct the signals. Section 5 gives the experimental results. Finally, conclusions and future works are described.

2. The overview of exposed optical incremental encoders

The configuration of an exposed optical encoder is illustrated in Fig. 1. The light beam from an infrared LED illuminates the scanning grating firstly. Then, the light is diffracted by the scale grating to produce a set of interference fringes at the detector plane. When the scale grating is moved relative to the reading head, the total light intensity at the photodiodes varies periodically. The signals provided by the photodiodes array are four sinusoidal current signals ($\pm I_S$ and $\pm I_C$) shifted 90°. Transimpedance amplifiers convert these currents to voltages (V_S+, V_S-, V_C+ and V_C-), which are the input sources of the proposed amplitude-to-phase converter.

The proposed converter includes signal pre-processing circuits, analog-to-digital converter (A/D converter) circuit, and interpolation and counting circuits. The voltage signals are conditioned by the signal pre-processing circuits, and then digitized to be processed in an FPGA. This FPGA provides timing signals, applies signal linearization procedure, recognizes moving direction, counts complete signal cycles, interpolates signals, and formats the output signals.

3. Operating principle of proposed converter

The interpolation and counting circuits is the core part of the proposed converter. Its schematic diagram is shown in Fig. 2. For a mathematical description, the two signals at the outputs of the signal pre-processing circuits can be expressed as:

$$V_S(x) = A_1 F_1 \left(2\pi \frac{x}{p} + \Phi_1\right) + B_1 \tag{1}$$

$$V_C(x) = A_2 F_2 \left(2\pi \frac{x}{p} + \Phi_2\right) + B_2 \tag{2}$$

where p is the period of the scale grating, x is the position and $0 \le x \le p$, A_1 and A_2 are the amplitudes, B_1 and B_2 are the background levels, Φ_1 and Φ_2 are the phase of the signals, and F_1 and F_2 are the functions that described the shape of the signals with $\min(F_\alpha) = -1$ and $\max(F_\alpha) = 1$, where $\alpha = 1, 2$. For the ideal case, the two signals are given as:

$$V_S(x) = A \sin\left(2\pi \frac{x}{p}\right) \tag{3}$$

$$V_C(x) = A \cos\left(2\pi \frac{x}{p}\right) \tag{4}$$

where A is the amplitude of the signals that $A_1 = A_2 = A$.

By employing the absolute values of the signals $V_S(x)$ and $V_C(x)$, and computing the ratio of their difference with their sum, a nearly piecewise linear signal is generated:

$$V_1(x) = \frac{\left|V_S(x)\right| - \left|V_C(x)\right|}{\left|V_S(x)\right| + \left|V_C(x)\right|} \tag{5}$$

The waveform $V_1(x)$ compares reasonably well with a normalized perfect triangular waveform $Trig(x)$:

$$Trig(x) = \frac{4}{\pi}\left|\sin^{-1}\left[\sin\left(2\pi \frac{x}{p}\right)\right]\right| - 1 \tag{6}$$

and its deviation from $Trig(x)$ is given by:

$$E_1(x) = V_1(x) - Trig(x) \tag{7}$$

The pesudolinearity of the sections of $V_1(x)$ suggests that this signal may be used for the estimation of the displacement x using simple linear equations. To further linearize the output signal, the idea of using a compensation signal has been proposed by Benammar et al. [1,7,8]. In the following work, we also focus on the construction of a compensation signal. As depicted in Fig. 3, the deviation $E_1(x)$ is within $\pm 9.05\%$ and has a piecewise distorted sinusoidal shape.

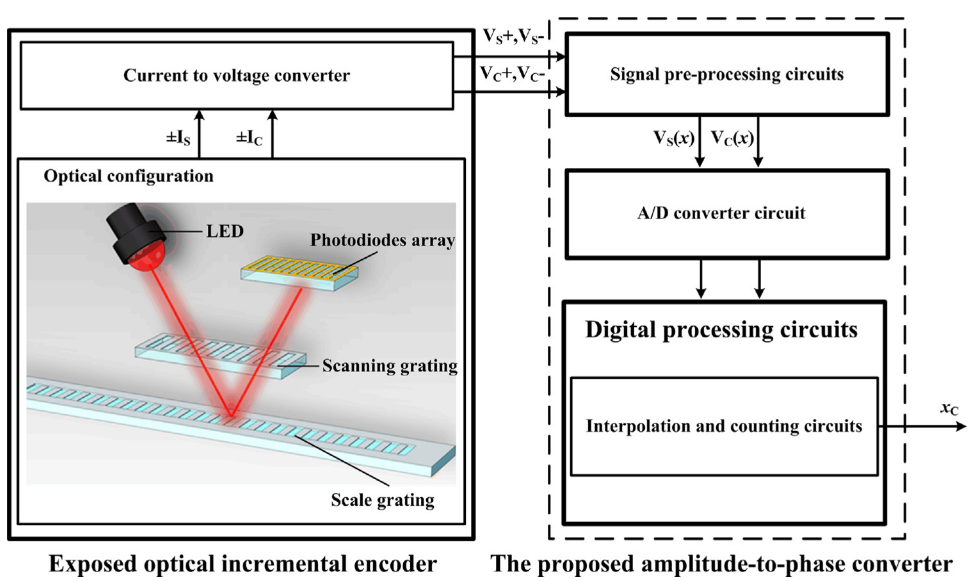

Fig. 1. Scheme of an exposed optical incremental encoder and the proposed amplitude-to-phase converter.