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A robust sub-pixel subdivision algorithm for image-type angular displacement measurement

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ABSTRACT

The use of an image detector to receive grating images and measure angle displacement via image processing is a relatively new technique, which yields higher resolution and better precision than the traditional moiré fringe method. To improve the robustness of image-type angle measurement, this paper proposes a robust sub-pixel subdivision algorithm based on the least square method. Firstly, by analyzing the characteristic of grating image, a new subdivision algorithm is established based on the least square method. Secondly, the simulations of robustness are completed to prove the performance in theoretically. Lastly, the proposed algorithm is used in a typical image-type angle sensor to test the performance in real case. By test, the proposed method is shown to be more accurate and with better robust than the traditional algorithm (centroid algorithm). In a typical image-type angle sensor, it successfully achieves a resolution of 0.62″ (21-bit), 2^{13}-fold subdivision resolution, and precision of 12.85″. The results presented here may provide a theoretical and technological foundation for further research on small-size, high-resolution photographic rotary encoders.

1. Introduction

Photoelectrical angle-displacement measurement is a high-resolution, high-precision technology which combines optical, mechanical, and electronic functions. Angle sensors are crucial components of many different instruments [1]. Current angle sensors use index grating and scale grating to form moiré fringe, change the moiré fringe to a photoelectrical signal through the receiving element, and realize angular measurement via microprocessor. Many sensors work very well using moiré fringe: The absolute encoder designed by the Heidenhain Company, for example, can reach 27-bit resolution [2]; a likewise large in size, ultra-high resolution absolute encoder was designed by the Goddard Space Center as an optical pattern recognition and image processing technology [3]; the 25-bit absolute encoder designed by Chinese Chengdu Institute of Optics and electronics performs well [4]; and the high-resolution encoder designed by the Chinese Changchun Institute of Optics, Fine Mechanics and Physics reach 0.01″ resolution [5]. These devices all used large grating. Achieving high-resolution measurement with smaller grating is much more difficult.

The digital imaging process may be better served by image detectors equipped to measure angle displacement [6–11]. Researchers have indeed used image detectors to receive grating images and achieve high resolution angle displacement measurement via image processing; scholars in the U.S. [12,13], Serbia [14], Japan [15], Spain [16], Korea [17], China [18,19] and other countries have made notable achievements regarding image type encoders. There have been few studies on subdivision and compensation methods for image detectors, however.

Image type angle measurement technology is a recent advancement for distinguishing disk reticle images to realize high-resolution and high-precision measurements [20]. The principle is illustrated in Fig. 1.

As light passes through the grating, the grating pattern projects onto the linear image sensors. In the process circuit, grating grooves are distinguished and the angle position measure with the subdivision algorithm. Angle subdivisions can be calculated intuitively by this method as-assisted by digital image processing technology. In a previous study, we achieved 1.24″ resolution and 14.6″ measurement precision with grating diameter of 38 mm.

We found those image noise and lens defocuse are the main factors impacting the subdivision algorithm results. Although digital image filtering can filter some noise, it also causes some angle information to be lost. For these reasons, our primary goal in conducting the present study was to secure a new angle subdivision algorithm with robustness to noise and defocusing.

In this paper, we analyzed the imaging characteristics of grating grooves and established a robust subdivision algorithm based on the least square method accordingly. This algorithm can minimize the influence of image noise and lens defocus effectively; it features accurate recognition ability and strong adaptability. We applied the algorithm in

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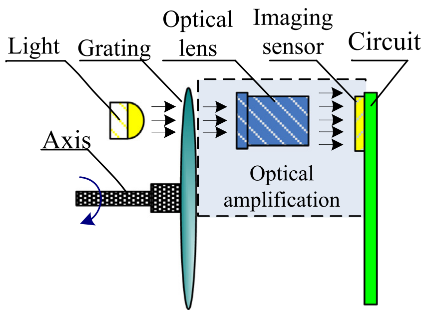

Fig. 1. Angle measurement principle.

an angle sensor and achieved 2^{21} resolution and 12.85″ precision when the grating diameter was 38 mm.

The remainder of this paper is organized as follows. In Section 2, the robust subdivision algorithm is proposed based on the analysis of grating-grooves images. In Section 3, we demonstrate the performance of the algorithm by simulation. Section 4 presents a series of test results. Conclusions are provided in Section 5.

2. Robust subdivision algorithm

Image type angle measurement requires the use of a grating which contains code lines and subdivision reference lines. We inserted reference lines among encoding lines. The code lines are according to shifting coding. The subdivision reference lines are 2^n equal-wide lines distributed uniformly on the circle. Because the lines have a certain width, it is crucial to accurately calculate the center during subdivision. An image of three neighboring subdivision reference lines received by the linear image detector is shown in Fig. 2.

In Fig. 2, the border of a subdivision reference line is not saltatorial and contains three areas: Top, transition, and bottom. The pixels in the top and bottom are relatively stable; the pixels in transition change considerably. The transition and top all include angle information. The traditional calculation method involves the use of a centroid algorithm to calculate the center:

$$R = \frac{\sum_{x\in N} p(x)g(x)}{\sum_{x\in N} p(x)} \tag{1}$$

where N is window size, g(x) are the positions of every pixel in N window, and p(x) are pixel values. This arithmetic can filter noise properly via an average algorithm. The size of N window significantly influences the result of the centroid algorithm. The center position of the image is R_0 and the two subdivision reference lines on either side of the image center are R_1 and R_2, as shown in Fig. 3.

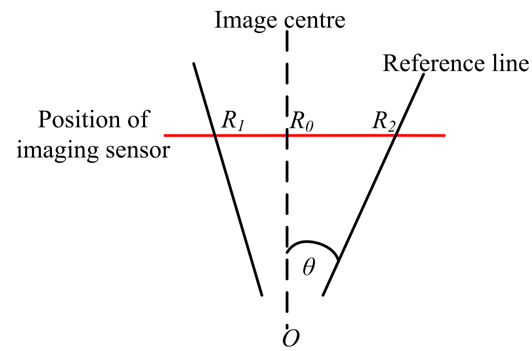

Fig. 3. Calculation with two reference lines.

Set 2^n as the quantity of subdivision reference lines in one circle. When n is sufficiently large (n > 7), $(R_2\text{-}R_0)/(R_2\text{-}R_1) \approx \angle\theta/\angle R_1OR_2$. The measured angle subdivision value can be calculated as follows:

$$\theta = \left| \frac{R_2 - R_0}{R_1 + R_2} \cdot \frac{360°}{2^n} \right| \tag{2}$$

Because the values of R_1 and R_2 are calculated based on the actual window N in Formula (1), this subdivision arithmetic is highly accurate and steady.

We established a new subdivision algorithm to ensure accurate center of reference line information in Formula (2). By analyzing reference lines, we determined a two-fold function is appropriate to fit the image of one reference line. The function is expressed as follows:

$$f(x) = ax^2 + bx + c \tag{3}$$

Where {a, b, c} are coefficients. To fit one subdivision reference line, the difference of squares sum between f(x) and p(x) must reach a minimum in window N:

$$M = \sum_{x\in N} [f(x) - p(x)]^2 \tag{4}$$

To determine whether M is minimal, we calculate partial derivatives of a, b, c, and let the partial derivative be zero:

$$\frac{dM}{da} = 2\sum_{x\in N} [ax^2 + bx + c - p(x)]x^2 = 0 \tag{5}$$

$$\frac{dM}{db} = 2\sum_{x\in N} [ax^2 + bx + c - p(x)]x = 0 \tag{6}$$

$$\frac{dM}{dc} = 2\sum_{x\in N} [ax^2 + bx + c - p(x)] = 0 \tag{7}$$

For easy calculation, Formulas (5–7) can be written as follows:

$$\begin{aligned} &(A_1 - A_3C_1)a + (B_1 - B_3C_1)b = D_1 - D_3C_1 \\ &(A_2 - A_3C_2)a + (B_2 - B_3C_2)b = D_2 - D_3C_2 \\ &c = D_3 - A_3a - B_3b \end{aligned} \tag{8}$$

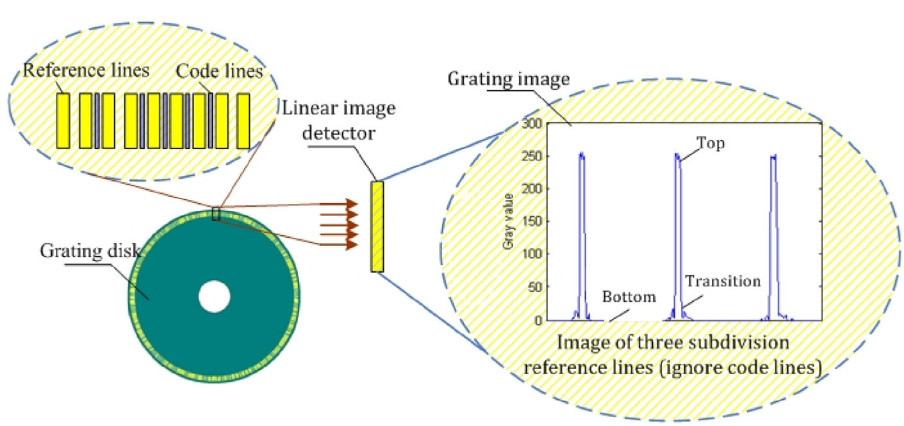

Fig. 2. Image acquisition principle. (The code lines is not considered in this paper).