Development of a methodology of estimating limits of oscillations of optical system of photoelectric rotary encoders

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Abstract. The development of optical sensors with rotating mechanism requires estimation of oscillations limits. Although some work has been done on to linear encoders, there’s no information on such approaches related to rotary encoders. This manuscript proposes a computational approach of estimating oscillations limits of optical systems of rotary encoders. The approach is based on machine computations of waveforms modified by shifting position of one of discs, and rotates not around main axis of optical system. For estimations of oscillations during computations, one of optical discs translated against optical axis of optical system to perform occlusions, accounting differences in light distribution with oscillations presented. As the result of applying of methodology, computer program described and tested to calculate limits of hypothetical optical system, as well as its predictions were confirmed by comparison with behavior of real rotary encoder. This data was achieved with fewer computations, compared to classical calculation methods of light propagation. Developed methodology allows creating computer programs for estimating limits of oscillations within reasonable timeframe.

1. Introduction

An optical encoder is a kind of angular sensor, as shown in figure 1, which is an opto-mechanical-electronic device transforming a light distribution into set of electrical signals, that can be used to define the relative position between a reading head and an angular scale [1]. High accuracy, wide measurement range, high response frequencies, light weight and high resolution of optical encoders leads to the fact that such type of sensors are widely used in modern military, aerospace, bioscience and other applications [2-5].

Mathematical modelling is a way to achieve predictable solutions, but it is not an easy computational task, especially light propagation and distribution [6]. Existing methods for fast illuminations calculations are mainly used in the film and game industries. Real time solutions of global illumination provide up to 180 frames per second according to sources [7,8], which is not enough for encoders. For example, a 11-bit encoder needs $2^{11} \times 10 = 20480$ frames (10 for interpolated data between sectors), which takes 2 min for rendering by system with theoretical performance of 708.5 GFLOPS [7,8] to achieve light data for one revolution. In order to find limits of oscillations it requires at least another 10 computational iterations that leads to increasing machine time up to 20 minutes. Such time requirement may sound insignificant, unless we are talking about more precise encoders. To render 25-bit encoder it takes up to half of a year.
The development of methods for calculating illumination is aimed primarily at approximations to increase the speed of calculations with the smallest possible decrease in accuracy. For the described problem, increasing the speed is not the goal, goal is to find the limits in a reasonable time. Coarsening of the results could be critical in the problem of estimating the limits of oscillations. Thus, these solutions may not be as trustworthy as needed and still not provides fast enough methods for per-frame-computable global illumination. These approaches for encoders are unrealistic for years from now on [8]. The aim of this paper is to design a methodology for reasonably fast and adequately precise analysis of oscillations in rotary encoders.

2. Methodology and experiments
Proposed method is based on calculations of waveforms of illumination of photosensitive elements. As long as physically correct computation of waveforms is not a viable solution for a present time, a number of approximations are needed.

Approximations involved:
1. Light propagate as flat parallel beam.
2. No interference.
3. No diffraction.
4. No Doppler effect.
5. All photodiodes characteristics are identical.
6. All LED’s characteristics are identical.
7. No thermal drift of parameters.
8. No light propagation delay (infinite speed of light).
9. No electrical delay.
10. Code disc is isotropic.
11. Only radial oscillation occurs.

After these assumptions, problem, instead of 3d, could be presented as 2d-solution. To form waveforms, it is necessary to calculate the area of the illuminated part of a 2d shape. The illuminated part is obtained by the intersection of two shapes, a code disk and a mask (figure 2).

A properly working encoder should provide data for every possible resoluted sector during revolution, with no miss (consistency of code), and, if revolution made into one direction, output code should be monotonous.
Figure 2. Some random: (a) mask; (b) intersection; (c) code disc.

The main idea is to form waveforms of photodiodes during one revolution, which could be used as input for model of encoder, and check for consistency and monotone. Waveforms are formed by dividing actual light flow through discs on maximum possible light flow. Resulting relative unitless values are used by logic model of encoder. Since there’s no universal direct means to assess limits of oscillations, bisection method is proposed [9]. Model provides binary output, so it could be parsed consequently by timeframes and checked for consistency.

If the data matches the correct code, then they are considered passed and oscillation value could be raised. On the other hand, in case of code error, oscillations should be reduced. After that, procedure repeats with adjusted oscillation values. This leads into iterative process to achieve target accuracy.

3. Results and discussion
As an illustration of methodology, ideal logic model of 11-bit Gray code encoder is presented in figure 3. It displays scheme of encoder designed in Matlab-Simulink. The model decodes Gray code into binary one.

Figure 3. Gray to binary encoder logic scheme.

This example was chosen to illustrate applications of methodology as simple and viable solution, which is easy to implement. The methodology could be applied to any encoding algorithms, not limited to Gray code or any other possible solution, including not invented yet encoding techniques.
As an optical system, 11 track code disk is proposed (figure 4a). To be closer to real encoders slits onto slit disk had been rotated onto equal angles (red slits in figure 4b). Also, code disk’s tracks rotated onto corresponding angles to match slit’s transformation (shown at figure 4b). Such transformation doesn’t change Gray code, but makes optical system way more isotropic to oscillations.

![Figure 4](image)

**Figure 4.** Topology of a code disk (blue) and mask (black and red) of 11-bit Gray code encoder before (a) and after (b) transformations.

For calculations, a program on Matlab language had been made. Oscillations simulated by moving code disk relative to reference point by X axis (arrow direction in figure 3), with starting value equal to the width of a single track (0.8 mm). As input data, it uses required accuracy of oscillations of optical system and encoder’s digit capacity.

Script forms code disk and corresponding slit disk. Radius of internal track had been set at 13.5mm, with 0.8 mm track width and 0.2 mm space between tracks. Script creates Gray code by recursion to required bits. Result array of binary numbers then used to create poly shapes on 1 and empty spaces on 0. All resulting shapes are unified into one. It could be seen that minimal slit presented as trapezoid, which could also be an assumption of proposed methodology, reducing its accuracy. However, area of etalon sector is:

$$S_{\text{sect}} = \frac{n^\circ}{360^\circ} \times \pi \times (r_2 - r_1)^2$$  

(1)

where $S_{\text{sect}}$ is an area of such shape, $r_1$ and $r_2$ – radii to origin point, $n^\circ$ – angle in degree.

Compared to trapezoid with area:

$$S_{\text{trap}} = \frac{\sin \left( \frac{2 \times n^\circ \pi}{180^\circ} \right) + \sin \left( \frac{2 \times n^\circ \pi}{180^\circ} \right)}{2} (r_2 - r_1)$$  

(2)

For described case with 11-bit encoder, formulas (1) and (2) give difference between methods of area calculation is about 0.037%, which considered as insignificant.

As it could be seen in figure 5, there’s a spike in what should be monotonous code. This represents an error in generated binary code. Provided with this data causing error track elements could be located (figure 6). In figure 6, code disk rotated to error’s position. Dark blue thin lines show unbiased position of code disk.
So, there are results of mathematical modeling and limits found by proposed methodology. For described optical structure of code disc for 11-bit Gray encoder the result is 33 um with inaccuracy of 0.25 um. To achieve this results, 11 iterations of script were needed, takes ~253 seconds to compute on 8 core 4GHz CPU, with rated performance of 546 GFLOPS.

To verify these results data from a real encoder was acquired. This real encoder uses other coding method and couldn’t be compared with shown example. So our example was modified to provide phase shifted signals from outer track. It was made by adding 3 slits to mask on the outer track, at about 90 degrees in-between. Ideal waveforms with zero oscillations of those signals shown at figure 7. After allying oscillations, computed signals change their form (figure 8). As it shown in figure 9 close to real waveforms were computed. Differences caused by electric capacitors existing in real encoder are results of smoothing waveforms.
It could be seen that if oscillations are close to limits, there are significant deformations in what should be identical phase-shifted signals. This effect is predicted by modeling.
4. Conclusion
The proposed method allows for a reasonable time to calculate the oscillations of the optical system of rotary encoders, giving verifiable results.

The proposed methodology is not based on any specific coding method, allows universal use and provides the ability to modify existing solutions at low cost, without changing the coding method or changes in the electrical part of the encoder. Also, taking into account the oscillations limits at the development stage will reduce the time and material costs for prototyping.

Methodology itself could be researched further to include various real-world properties, significant to accuracy, like dust, dirt, scratches, cracks, bends, and attrition. Also, additional mathematics can be introduced into the method to convert a three-dimensional to two-dimensional in a prebaked manner, which will lead not only to the analysis of radial displacement, but also to the toroidal analysis and their combination without additional computational use. As well, an interesting field of research could be phase dependency of initial translation for oscillations limits.

Manufacturing of a special encoder with variable measurable oscillations of optical system may be a good field of data acquisition for addressing inconsistencies in assumptions of the methodology. Further research could be in the field of algorithms for optimizing topology of such discs with higher oscillation tolerance, to compare results with assumptions of proposed approach.

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