# Development of an increment high-resolution optical displacement encoder

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*A novel increment high-resolution optical displacement encoder was proposed in this paper. The encoder is composed of a double-concave lens and a special designed optical grating with photo-diode in every slit. A light source set on the observable object is going through lens and the optical grating and received by the photo-diode. The relationship equation of lens is developed to design an optical mechanism which can enlarge the displacement of the observable object. From simulation results, a special designed optical grating is designed to compensate the deviations on the detecting surface and get the increment movement of the light source. The simulation results indicated that the optical mechanism with 5 mm stroke, which the lens radii of curvature of the incident and the exit surface on the lens were -0.625 cm and 1.25 cm, respectively, and the magnification was 50 times in imaging distance of 38 cm, could make the 10 nm movement intervals of light source to be about 500 nm movement intervals in the detecting surface. It should form an increment optical displacement encoder with a special designed optical grating. Last, an experiment is established to verify the possibility of the proposed structure.*

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**NOMENCLATURE**

$f$ = focal length of the lens
$n$ = refracting power of the lens
$n_m$ = refractive index of the surrounding environment
$R_1$ = radii of curvature of the incident surface of the lens
$R_2$ = radii of curvature of the exit surface of the lens
$d$ = thickness of the lens
$s$ = initial position
$s_1$ = new position
$\Delta s$ = distance between $s$ and $s_1$
$d$ = width of the lens

## 1. Introduction

Since the miniaturization of industrial products, there are some micro/nano-scale machines being proposed to manufacture these products by non-MEMs technology. Thus, the precision of measurement systems is more rigorous, and to develop a sub-micro- even a nano-level measurement system is becoming more necessary and importantly. Optical encoders are indispensable devices for precise displacement measurements in tool machines [1]. At present, the optical encoders can be separated into two major types: the diffractive optical encoders and the geometrical optical encoders [2, 3]. The measurements of the diffractive optical encoder are used widely for displacement metrology. Using a light emitting diode (LED) as the coherent light source and moving the grating of the object to modulate the phase of the light which is produced by the diffraction effect. The photodetector transfers the light signal into electrical signal after optical interference. As a result of the slit width of the grating is direct proportion with the resolution of the system, we can decrease the pitch of the gratings under the premise of there are light diffractions.

The geometrical optical encoders are wildly used in the tool machines for linear displacement detecting. They are using Moiré encoders in displacement measurements [4]. Such geometrical optical encoders normally consist of a LED, grating, index grating, phototransistor, and so on. The optical principle of the geometrical optical encoders can be explained theoretically by the grating imaging [5]. However, the restriction on the resolution of the geometrical optical encoder is about 100nm [6-8]. This is because the effect of the diffraction with the grating induces the signal to noise ratio being decreased. So there are restrictions on the distance between the gratings of the geometrical optical encoders.

An increment optical displacement encoder with 10 nm resolution by a double-concave lens was proposed in this paper. The increment optical displacement encoder was composed of a laser light source, an optical mechanism, and a special designed optical grating with photo-diode in every slit. We designed the optical mechanism by geometrical optics to change the paths of light, and then to get a more visible position in the position of the detect surface to improve the measurement accuracy. Firstly, we used the equations of thick lens to develop the relationship between the rays of light and the radii of curvature of the lens. Because the light will be refracted twice after entering the lens, the same primitive displacement of the light in the different input positions will not have the same output displacement and the differences will be enlarging as the position of the light entering the lens is far away from the center of lens. Thus, we designed special designed optical grating to compensating the deviations on the detecting surface and getting the increment movement of the laser light source to form the system. A prototype of the optical mechanism is established to verify the possibility of the optical encoder.

## 2. Principle

Fig. 1 shows the schematic diagram of the increment optical displacement encoder which is designed in this paper. The proposed increment optical displacement encoder can be divided into two parts: movable part and fixed part. The movable part is composed of an observable object, a light source and two lenses. The green coherent light source which is placed on the observable object is a laser diode. Lens A and B are using to adjust the laser light to be more tiny and parallel. Laser light from the movable part is going to be more thick by going through the lens C. An optical grating D is designed to compensate the deviations on the detecting surface and the phototransistors E will get the increment movement of the light source.

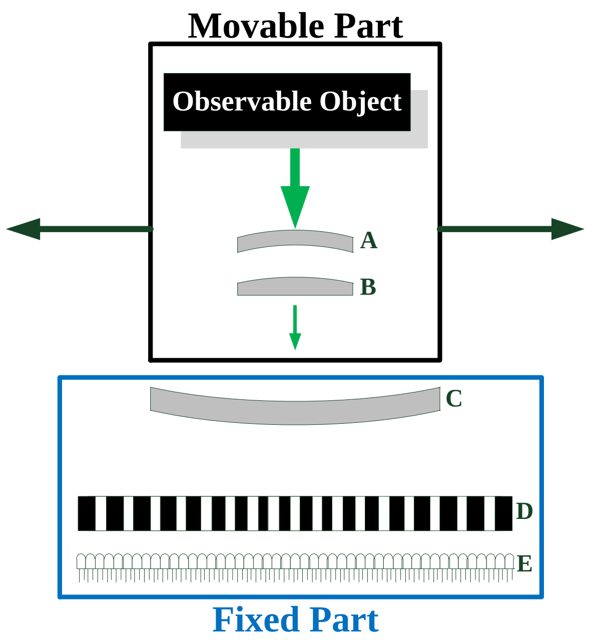


Fig. 1 Schematic illustration for the proposed increment optical displacement encoder

From the equation of thick lens, the relationship of the focal length of the lens and the radii of curvature of the incident and the exit surface of the lens can be expressed as:

$$\frac{1}{f}=\left(\frac{n}{n_m}-1\right)\left[\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2}\right] \tag{1}$$

Where $f$ is the focal length of the lens, $n$ is the refracting power of the lens, $n_m$ is the refractive index of the surrounding environment, the $R_1$ and $R_2$ are the radii of curvature of the incident and the exit surface of the lens, respectively, $d$ is the thickness of the lens.

Then, the relationship between the light source and the imaging position can be expressed as the function of $f$. The geometrical relation is shown in Fig. 2. Thus, if a light source horizontally moved from initial position $s$ to the new position $s_1$, the distance between s and $s_1$ is $\Delta s$, then the distance $s$ of the light source passed through the concave lens and refracted projecting on the imaging position can be calculated as:

$$s'=\left\{sh'\left(\frac{1}{n_m}-1\right)\left[\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2}\right]\right\}+s \tag{2}$$

And

$$s_1'=\left\{s_1h'\left(\frac{1}{n_m}-1\right)\left[\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2}\right]\right\}+s_1 \tag{3}$$

If we set $\varepsilon = \Delta s' / \Delta s$, then the relation of the displacement of light in the initial position and imaging position can be calculated as:

$$\Delta s'=s'-s_1'=(s-s_1)\left\{h'\left(\frac{1}{n_m}-1\right)\left[\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2}\right]\right\}+1 \tag{4}$$

$$\varepsilon=\frac{\Delta s'}{\Delta s}=\frac{s'-s_1'}{s-s_1}=\left\{h'\left(\frac{1}{n_m}-1\right)\left[\frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2}\right]\right\}+1 \tag{5}$$

According the formula (5) the magnification is approximately inverse proportional to the radii of curvature of the lens, shown as equation (6), so we can design the radius of double-concave lens to modify the paths of light to magnifying the deviations on the detecting surface and getting higher measuring accuracy.

$$\varepsilon \propto \frac{1}{R_1}-\frac{1}{R_2}+\frac{(n-1)^2 d}{nR_1R_2} \tag{6}$$

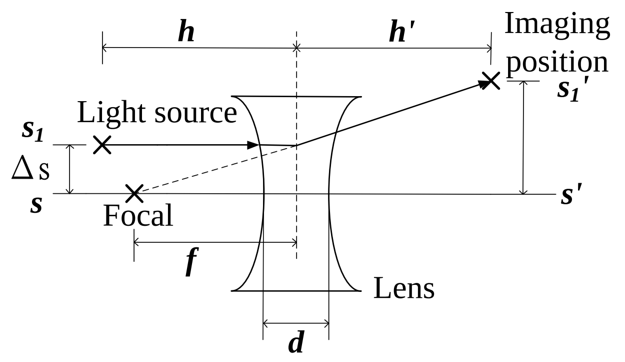


Fig. 2 Relationship between the light source and imaging position through a lens

## 3. Simulation

The simulation is Fig. 3 is the simulation result of the imaging refraction process a light source drift. When the light source is moving far away from the origin, the magnification of the light source radius is becoming larger.

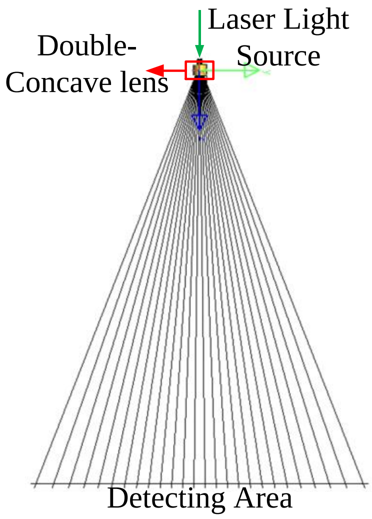


Fig. 3 Simulation result of the light source through the double-concave lens

The different radii of the curvature of the lens to obtain the relationship between the magnification and the position are shown in Fig. 4. Radii of curvature of the lens are $R_1$=-6.25mm and $R_2$=12.5mm for curve 1, $R_1$=-6.25mm and $R_2$=6.25mm for curve 2 and $R_1$=-6.25mm and $R_2$=-12.5mm for curve 3, respectively. The imaging distances are 380mm, 160mm and 1260mm, respectively. When the imaging distance becoming more far from the lens, the radii of the light source will become more larger.

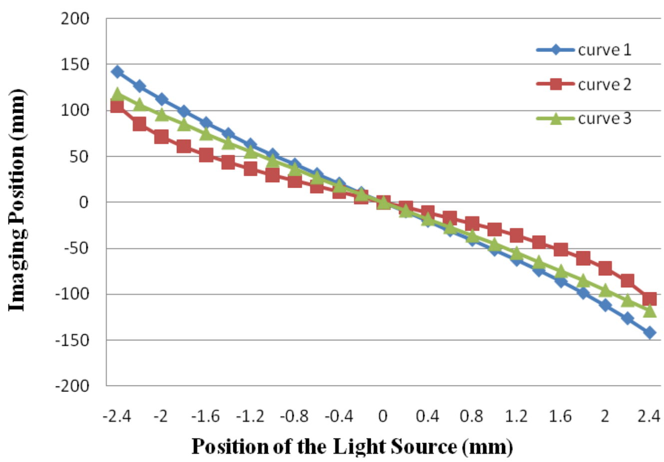


Fig. 4 Position relations of the light source and the imaging for three lenses with different radii of curvatures

The light source radii will become larger because the distance of the imaging position and the distance of the light source from the center. By simulation results, an optical grating is designed in order to make the laser light source become the staggered signal. The light source will go through the optical grating and received by the phototransistors, as shown in fig. 5. The ellipses with dark green and light green mean the light source is moving with 10nm displacement. Optical grating is designed according to the radii of the light source. The light source through the grating will divide into one path signal and two paths signal. Different signal received by the phototransistor will go through the logic gate and generate a square wave signal, as shown in fig. 6. Thus, we can get the increment movement of the laser light source from the square wave signal.

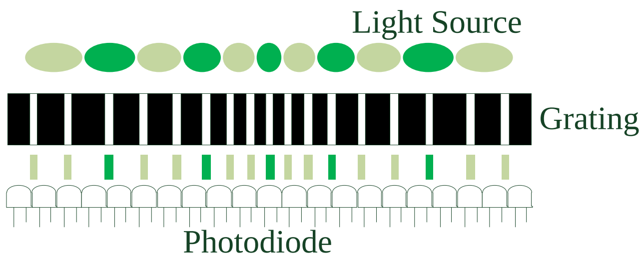


Fig. 5 The laser light source through the optical grating mechanism and received by the phototransistors.

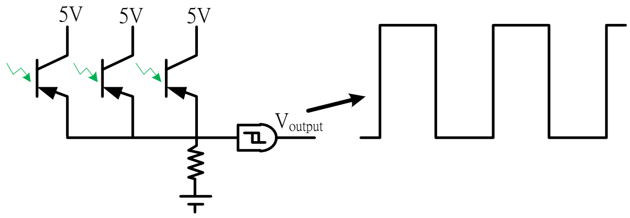


Fig. 6 Different light sources received by the phototransistors will generate a square wave signal.

## 4. Experiments

An experiment device is constructed in order to verify the possibility of the proposed increment high-resolution optical displacement encoder, as shown in fig. 7. The radius of the laser light source is 1mm and the radius of the light going through the lens is 10mm. The optical grating is set between the phototransistors and the fixed lens. When the laser light source moves from left to right, the illustration of the phototransistors voltage is show in fig. 8. The light after amplified through the optical grating which is show at the upper right corner of the fig. 8 is move from point A to point B. We can see the voltage of the phototransistors is shown as a sine wave signal.

The magnification factor of the lens which is used in this experiment is about 3 times. The displacement of the laser light source is about 6mm, and the displacement of the amplified light is about 20mm. The optical grating is designed by the amplified light. From the experiment result, we can make the light source to be a sine wave signal with the optical grating. With a logical gate, the sine wave signal can transfer to a square wave signal. Therefore, we can separate the displacement of the laser light source to numbers of the square wave signal, ex. separate 1mm displacement to a 1000 number of square signals.

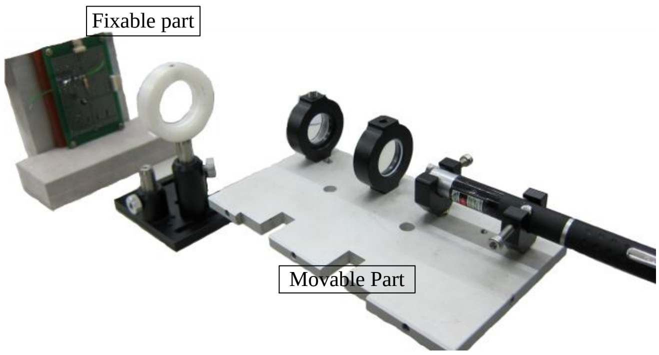


Fig. 7 Experimental setup, the movable part contains a laser light source and two lenses and the fixable part contains a lens and a phototransistors.

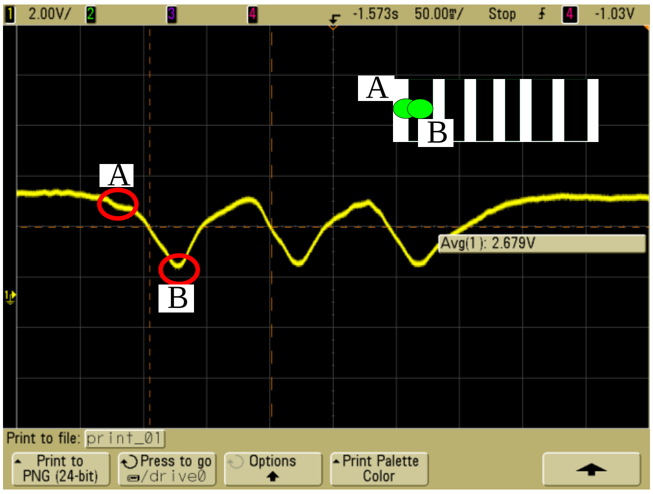

Fig. 8 Experimental result, the relationship with the light and the grating is shown at the upper right corner of the figure.

## 5. Conclusions

A novel optical mechanism structure of linear increment optical displacement encoder with high resolution was proposed in the paper. By the equations of thick lens, an optical mechanism was designed to change and modify the paths of light to get a more visible position change in the optical detector consisted by a well-designed non-equidistant optical grating and phototransistor to improve the measurement accuracy. The equations of thick lens are used to develop the relationship between the rays of light and the radii of curvature of the lens to form the optical mechanism system. Theoretically, the 10 nm displacement signal could be magnified by the measurement system to be a measurable signal on the phototransistors. The experiment shows the possibility of the proposed theorem. In precision machining, we can build an increment high-resolution optical displacement encoder with 10nm

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