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Optical Proximity Sensor by using Phase Information

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Abstract

In this paper, an optical proximity sensor based on measuring the phase shift of the modulated light reflected from the target object is described. The optical proximity sensors developed so far, have been based on detecting the intensity or timing of light reflected, but here, we made up the simple sensor based on measuring the phase shift of modulated light reflected from the object. It can measure the distance to the object and the inclination angle of the object without being affected by the reflection factor. The sensor is basically composed of two light sources and one optical detector, all of which face the target object. For distance measurement, two of the light sources are located asymmetrically around the detector and are driven by $\sin\omega t$ and $\cos\omega t$ signals. The distance is a function of the phase angle of the detected reflex light signal. For inclination-angle measurement, two of the light sources are located symmetrically around the detector. The inclination angle is a function of the phase angle of the detected light signal. Testing of a prototype sensor and signal-processing circuit demonstrated its effectiveness. This sensor, which can detect the situation of objects at close range, is particularly suited for use in flexible automation systems.

Key Words: robot sensor, proximity sensor, optical sensor, phase modulation, distance and angle measurement,

1. Introduction

External-sensing and sensory-control technologies are indispensable for flexible automation, which is needed when system conditions can vary. Systems using industrial robots require not only a global vision sensor and a dynamic tactile sensor, but also a proximity sensor that has the features of both vision and tactile sensors. A proximity sensor is a non-contact detector that measures the distance to and inclination angle of the target object as the robot approaches to within several mm of the object. This type of external sensor is particularly useful for robotic applications because it is both simple and versatile. Several types of detection methods have been developed for use in proximity sensors, including optical, electromagnetic, and ultrasonic methods. While each type has particular advantages, the optical-type methods are best suited for general applications because the detection head can be made smaller. Furthermore, they can be used to detect objects made of any type of material, and their detection range is the widest.

The most precise measurement is achieved by using laser-light interference, i.e., the phase shift or time delay between the projected light and the received light.[1)]

An example of a simple optical proximity sensor for robot control is a distance sensor that uses the intensity of the light reflected from the object.[2), 3)] Another uses a few aligned light sources that are activated sequentially. The timing of the light received through a pinhole gives the light path and the distance.[4)] While this method is not affected by the reflective coefficient of the object surface, it is structurally complex, and interpolation is needed to achieve high resolution, and measurement must be done continuously.

In this paper we describe a sensor that is fundamentally based on measuring the intensity of the reflex light and is not affected by the reflectivity or inclination angle of the object's surface. It can be used to measure both the distance to and the inclination angle of the object, which is often required to control the motion of a robot. The angle is measured by changing the lighting pattern, making this sensor suitable for practical use.

2. Principle of Distance Measurement

In this section we describe how the proposed proximity sensor uses phase information to measure the distance to the object.

As shown in Fig. 1, two light sources, LED1 and LED2, are located asymmetrically at α and β in relation to position γ of photo detector PHTR. We make three

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assumptions to simplify the sensor model.

(1) The light sources (LEDs) have wide directivity.

(2) The photo detector (a phototransistor) has sharp directivity.

(3) Reflection from the surface of the object is diffused, so that the illumination of the projected surface by the light sources is proportional to the cosines of the inclination angles. Also, taking the projected surface as a new light source, the brightness of its surface as seen from any direction is constant.

These assumptions are consistent with conventional sensor design and assembly, and only objects whose surface has a mirror reflection cause a problem. These assumptions are thus applicable to most potential objects. The effect of these assumptions on detection accuracy will be considered in a later section.

If the emitting powers of light sources LED1 and LED2 are G_1 and G_2, their contributions to the illumination of point P are,

$$L_1 = G_1 \cdot \cos\theta_1 / P\alpha^2 \quad (1)$$

$$L_2 = G_2 \cdot \cos\theta_2 / P\beta^2 \text{(Lambert's Law)}. \quad (2)$$

If the projected surface is considered a new light source, brightness Lp at point P is proportional to the product of total illumination and reflectivity C of the surface:

$$Lp = C \cdot (L_1 + L_2). \quad (3)$$

The light paths from points α and β to point P are given by distances *a* and *b* from the light sources to the photo sensor:

$$P\alpha^2 = a^2 + x^2 \qquad P\beta^2 = b^2 + x^2. \quad (4)$$

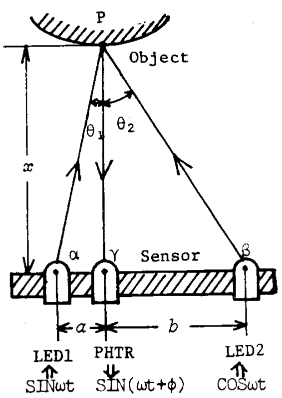


Fig. 1 Basic principle of distance measurement

The cosines of the projection angles are represented as

$$\cos\theta_1 = x / \sqrt{a^2 + x^2}\ ,\ \cos\theta_2 = x / \sqrt{b^2 + x^2}\ . \quad (5)$$

The brightness of each light source is modulated by two 90-degree phase-shifted sinusoidal signals (the light power changes sinusoidally). *A* and *B* are the amplitudes of the light sources:

$$G_1 = A \sin\omega t \quad and \quad G_2 = B\cos\omega t. \quad (6)$$

The luminous intensity of the target point, Lp, is obtained using equations (1) to (6).

$$Lp = C \cdot \{ \frac{A \cdot x}{(a^2 + x^2)^{3/2}} \sin\omega t + \frac{B \cdot x}{(b^2 + x^2)^{3/2}} \cos\omega t \} \quad (7)$$

$$= D \cdot \sin(\omega t + \phi) \quad (8)$$

Amplitude *D* and phase shift φ are expressed as functions of gap distance x and of the space distances between the LEDs and photo-detector PHTR, *a* and *b*.

$$D = C \cdot x \sqrt{\frac{A^2}{(a^2 + x^2)^3} + \frac{B^2}{(b^2 + x^2)^3}} \quad (9)$$

$$\phi = \tan^{-1}\{ \frac{B}{A} \cdot (\frac{a^2 + x^2}{b^2 + x^2})^{3/2} \} \quad (10)$$

Given the attenuation of the light power from point P to the photo-detector, the observed light power is

$$M = (K / x^2)\, D \sin(\omega t + \phi), \quad (11)$$

where K is a constant and φ is as given in equation (10).

Therefore, the phase shift of the reflected light signal is a function of the distance between the object's surface and the sensor and is not affected by the reflection factor of the surface. The relation between the distance, *x*, and φ is shown in Fig.2 , where the parameter is intensity ratio *B/A*.

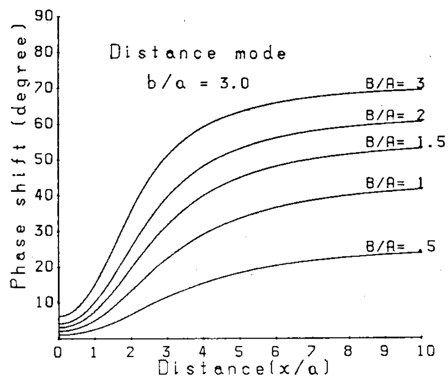


Fig. 2 Characteristics of distance sensor

3. Compensation for and Measurement of Inclination Angle

In the previous section, we considered the distance measurement for when the objective surface is perpendicular to the axis of the received light path. Here, we consider how the inclination angle affects the objective surface and introduce a method for measuring and compensating for the inclination angle.

In the basic sensor configuration for distance measurement, shown in Fig. 3, if the object surface inclines with angle δ, the detected phase changes. In this case, the brightness of observed point P is represented by applying the coefficients of $\cos(\delta-\theta_1)/\cos\delta$ and $\cos(\delta+\theta_2)/\cos\delta$ to the basic equations. We can then obtain Lp' by composing two factors,

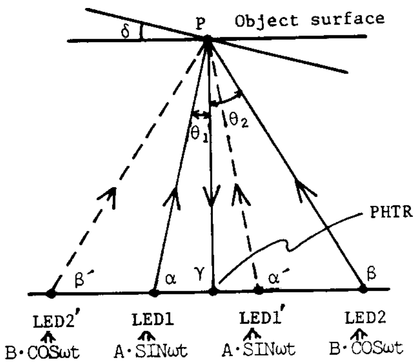


Fig.3 Compensation for inclination angle.

$$Lp' = \frac{C}{\cos\delta}\left\{\frac{\cos(\delta-\theta_1)}{a^2+x^2}\cdot A\sin\omega t + \frac{\cos(\delta+\theta_2)}{b^2+x^2}\cdot B\cos\omega t\right\}$$

$$= C\cdot\sqrt{A^2\left\{\frac{x+a\tan\delta}{(a^2+x^2)^{3/2}}\right\}+B^2\left\{\frac{x-b\tan\delta}{(b^2+x^2)^{3/2}}\right\}}\cdot\sin(\omega t+\phi') \quad (12)$$

and φ' is obtained as a function of x and δ,

$$\phi' = \tan^{-1}\left\{\frac{B}{A}\cdot\left(\frac{a^2+x^2}{b^2+x^2}\right)^{3/2}\cdot\left(\frac{x-b\tan\delta}{x+a\tan\delta}\right)\right\} \quad (13)$$

As expressed in equation (13), the effect of the inclination angle depends on the asymmetrical arrangement of the light sources. To compensate for the effect of the inclination angle, we add another pair of light sources, LED1' and LED2', symmetrically to the line P→γ, the solid line in Fig. 3. They are driven by signals Asin ωt and Bcos ωt. The brightness of point P in this case is given by

$$L'p_{1\text{-}2} + L'p_{1'\text{-}2'} = \frac{C}{\cos\delta}\left[\{\cos(\delta-\theta_1)+\cos(\delta+\theta_2)\}\cdot\frac{A\sin\omega t}{a^2+x^2} + \{\cos(\delta-\theta_1)+\cos(\delta+\theta_2)\}\cdot\frac{B\cos\omega t}{b^2+x^2}\right]. \quad (14)$$

$$= 2Cx\sqrt{\frac{A^2}{(a^2+x^2)^3}+\frac{B^2}{(b^2+x^2)^3}}\cdot\sin(\omega t+\phi) \quad (15)$$

Phase shift φ is equal to equation (10), so the effect of the inclination angle is compensated for.

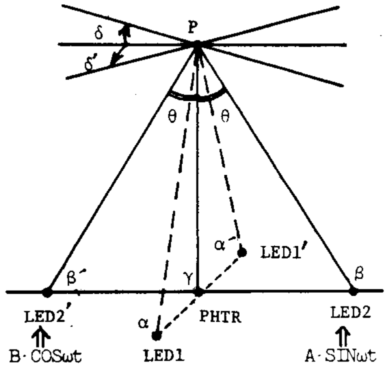


Fig. 4 Principle of angle measurement

Next, we describe the method for measuring the angle with the additional pair of light sources. Figure 4 shows the arrangement when the second pair of LEDs are positioned the same distance from the light detector (which means that the elements are positioned symmetrically in relation to the detector).

When LED2 and LED2' are driven by Asin ωt and Bcos ωt, respectively, phase shift φ'' of the received light signal is obtained using

$$Lp''' = \frac{C}{\cos\delta}\cdot\left\{\frac{\cos(\theta-\delta)}{b^2+x^2}\cdot A\sin\omega t + \frac{\cos(\theta+\delta)}{b^2+x^2}\cdot B\cos\omega t\right\} \quad (16)$$

$$= \frac{C}{(b^2+x^2)^3}\cdot\sqrt{A^2(x+b\tan\delta)^2+B^2(x-b\tan\delta)^2}\cdot\sin(\omega t+\phi'') \quad (17)$$

$$\phi'' = \tan^{-1}\left\{\frac{B}{A}\cdot\frac{(x-b\tan\delta)}{(x+b\tan\delta)}\right\} \quad (18)$$

The characteristics of φ'' are shown in Fig. 5. The equation for φ'' includes distance parameter *x*. Under conventional measurement conditions, both parameter *x* and δ are unknown, so the angle-compensated distance data is first determined, then used to obtain angle δ. In particular, if gap distance x and element-space distance *b* are set equal, inclination angle δ can be obtained directly from phase shift φ''' of the received signal:

$$\phi''' = 45^{\circ} - \delta \quad . \qquad (19)$$

To measure the inclination angle in another direction, a third pair of light sources are set on the orthogonal axis, the dotted line in Fig. 4. First, the original pair of LEDs are driven by sinωt and cosωt to detect angle δ, and then the another pair of LEDs which are on orthogonal direction are driven by sinωt and cosωt to detect δ around this direction.

By driving the inner pair of LEDs by sinωt and outer pair of LEDs by cosωt, the distance data are not affected by the directional inclination.

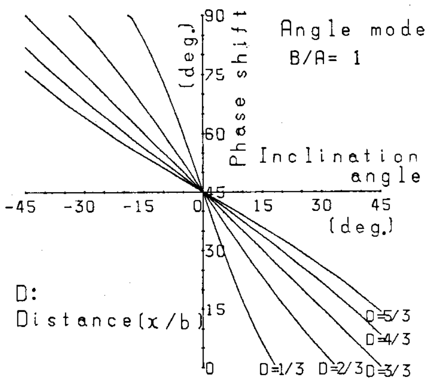


Fig. 5 Characteristics of angle sensor

4. Construction of Measurement System

The circuits used to measure the distance and angle are illustrated in Figure 6. Four LEDs are driven by a rectangular-wave generator, which is switched by a mode-select circuit. In distance-measurement mode, the two pair of LEDs are driven by sine and cosine signals to compensate for the effect of the inclination angle. In angle-measurement mode, the outer two LEDs set the same distance from the detector are also driven by sine and cosine signals.

The modes can be changed by using an internal or external signal. The signal from the phototransistor used as the light detector is amplified and filtered by a band-pass filter to extract the fundamental-frequency component. This signal is converted to a binary signal and compared with the standard signal to detect the phase difference. We use a binary counter to count the number of clock pulses in order to determine the phase difference; the data for distance and angle are obtained as an 8-bit parallel signal. For simplicity, a rectangular signal is used instead of a sinusoidal signal. By using filtering, only the fundamental-frequency component is extracted and processed, so the discussion of basic principle in section 3 is adopted as is.

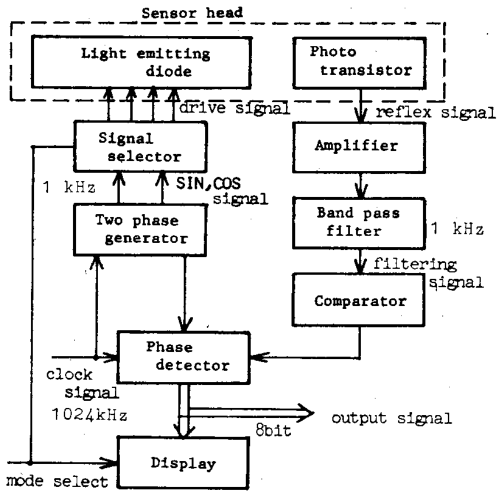


Fig. 6 Block diagram of detection circuit

Photo 1 shows the sensor head. Four GaAs infrared-light-emitting diodes and a Si phototransistor are arranged on a 10x10x5-mm base with *a*=10 mm and *b*=30 mm.

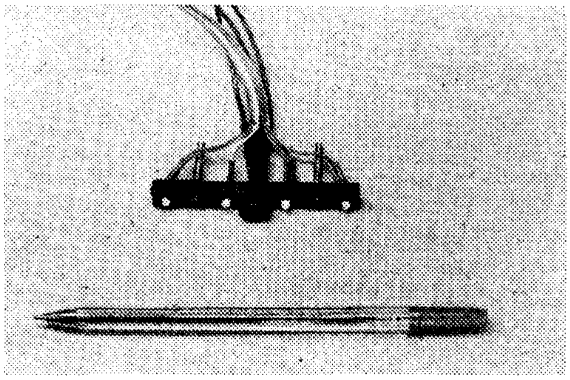


Photo 1 View of sensor head

We tested a prototype sensor and processing circuit by using white paper and a few bits of colored paper. The intensity of the LEDs was calibrated using a standard phototransistor. The reflective factor of the objective surface was determined by comparing it with that of white paper, which has a factor of 100%.

In the distance measurement, the phase shift increased monotonously from 10 to 60 mm, as shown in Fig. 7. Within this range, the measurement error did not exceed ±2 mm. This error can be explained by differences in the reflective factor and the existence of noise in the measurement system.

Figure 8 shows the effects of the inclination angle and compensation. The compensation suppressed the error in measuring the distance to within 4% in the range of inclinations from -30° to 30° .

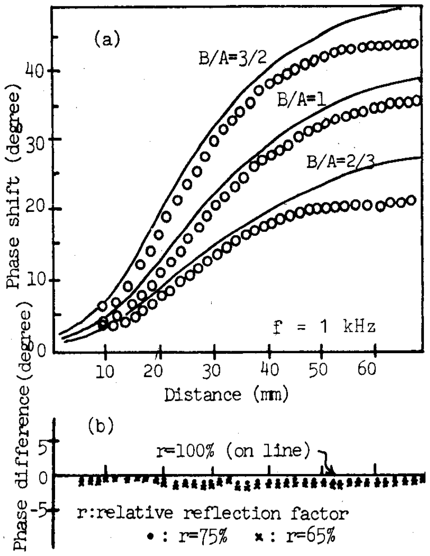


Fig. 7 Experimental data of distance measurement

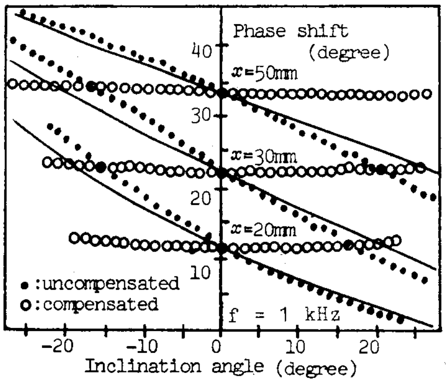


Fig.8 Effect of compensation on distance-measurement

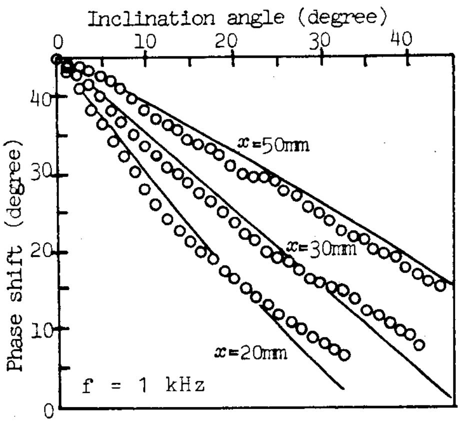


Fig. 9 Experimental data of angle measurement

In the angle measurement, the slope of the phase-shift vs. inclination-angle line changed with the distance, as shown in Fig. 9. The data curves crossed at the point of 45 ° shift. The linearity error was under 9%, and the dispersion was under ± 2%. The solid lines were calculated using equation (18).

5. Consideration of Accuracy and Characteristics

In this section we consider the effect of element directivity, the effect of diffused reflectivity, and the transient characteristics of the sensor.

5.1 Effect of element directivity

In Section 2, we assumed that the light sources have wide directivity and that the light detector has sharp directivity. Here we discuss the effect of the directivity of the elements actually used in the experiment

First we consider the effect of the directivity of the LEDs. Suppose the relative intensity distribution is written as F(η) , where η is the angle measured from the front line. In distance-measurement mode, the intensity difference is caused by differences in angle η , so *B/A* in equation (10) should be changed to,

$$(B/A)^* = (B/A)\{\, F(\tan^{-1}\frac{b}{x}\,)\,/\,F(\tan^{-1}\frac{a}{x}\,)\}\,. \quad (20)$$

Calculation using the element value obtained experimentally changes the phase shift to that shown by curve ① in Fig. 10.

Next we consider the effect of the actual sensitive area of the detector. The phototransistor observes the light reflected from a certain area; the angle of sensitivity is assumed to be ψ, and within this angle, the sensitivity is regarded as constant. The mean illumination of the detected area is given by,

$$L1^* = \frac{E}{2Y}\int_{-Y}^{Y}\frac{x\cdot G_1}{\{x^2+(a+y)^2\}^{3/2}}\,dy\,. \quad (21)$$

where E is a constant, Y is the distance from the observed area centered on the objective surface, and $Y = x\tan(\psi/2)$. Using the area of phototransistor sensitivity, determined here as ψ=10 ° , we calculated the error shown as ② in Fig. 10.

This error was less than 1/20 that due to the effect of the LEDs, so it is not necessary to make any correction to the directivity of the detector. For reference, the error for ф =20 ° is shown as ③ in Fig. 10.

5.2 Effect of diffused reflectivity

What if the object surface does not have diffused reflection? Consider the situation where a light detector is placed so that it is perpendicular to the object's surface, the light sources are rotated, and the intensity of the light at the detector is measured at several angles. By comparing this data to the cosine characteristics, we can evaluate the diffusion characteristics. The phase difference calculated using the actual reflection of the surface used in the experiment is shown as ④ in Fig. 10. The use of coated paper increased the effect of the reflection characteristic on the error (Fig. 10 ⑤).

Under the same conditions, in the angle-measurement mode, the phase difference was about 9% less than for the colored paper used in the experiment and almost 20% less for the coated paper.

These results indicate that the difference between the calculated and measured values was due to the light sources not having wide directivity and the reflection from the objective surface not being completely diffused.

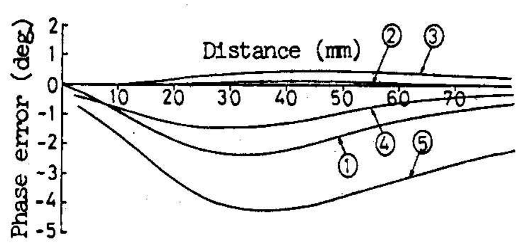
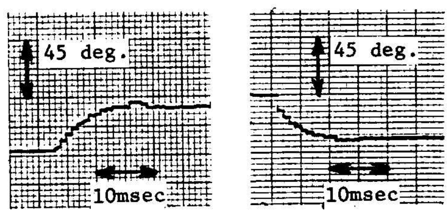


Fig.10 Phase error of the sensor



(a) Distance to angle mode (b) Angle to distance mode

Fig.11 Step response of the sensor

5.3 Transient characteristics of sensor

Finally we consider the transient characteristics of the sensor. The response of the distance and angle measurements is affected by the 1-kHz sampling period and by the delay of the photo sensor and filter. By switching the measurement modes, we can give an equivalent step input of the phase shift to the circuit. The observed step response is shown in Fig. 11, which shows that this sensor can be represented as having a first order delay with a 4-ms time constant. This time response is short enough for the sensor to be applied to conventional servo mechanisms.

6. Conclusion

We have proposed a new type of optical proximity sensor that can measure the distance from the sensor head to the target object, and also the inclination angle of the object surface. And the characteristics of the sensor are discussed. This sensor consists of six light sources arranged asymmetrically or symmetrically around a photo detector. They are driven by a two-phase sinusoidal signal. By detecting the phase difference of the reflected light signal, both the distance and the inclination angle can be obtained. The measured data is not affected by surface reflectivity, so it can detect both the distance and angle very quickly. The sensor head is very simple and small, and the driving and processing circuits are simple. The fundamental characteristics obtained by measurement experiments demonstrated the effectiveness of the proposed sensor.

Future work includes application of this sensor to objects with mirror reflectivity, widening the measurement range, and improving the measurement accuracy.

The proposed sensor is applicable to two types of robot control:

(1) robot arm and hand pose control, such as tracking moving objects, surface tracing of three-dimensional curved objects, and approaching objects at a constant angle by setting the sensor on the top of the hand;

(2) robot wrist and hand motion control, such as grasping objects adaptively by measuring the position, shape, and inclination angle by setting the sensor inside the hand.

The sensor is especially suitable for application (1) because with it the robot hand can easily keep a constant gap and a constant relative angle while moving around the object.

We are now working to improve the sensor and investigating potential applications. We will present the results of this work at the next opportunity.

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