One Idea on a Three Dimensional Measuring System Using Light Intensity Modulation

Ikumatsu Fujimoto, In-Ho Cho, Jeong-Hyeon Pak, and Young-Sik Pyoun

Abstract: A new optical digitizing system for determining the position of a cursor in three dimensions(3D) and an experimental device for its measurement are presented. A semi-passive system using light intensity modulation, a technology that is well known in radar ranging, is employed in order to overcome precision limitations imposed by background light. This system consists of a charge-coupled device camera placed before a rotating mirror and a light-emitting diode whose intensity is modulated. Using a Fresnel pattern for light modulation, it is verified that a substantial improvement of the signal to noise ratio is realized for the background noise and that a resolution of less than a single pixel can be achieved. This opens the doorway to the realization of high precision 3D digitized measurement. We further propose that a 3D position measurement with a monocular optical system can be realized by a numerical experiment if a linear-period modulated waveform is adopted as the light-modulating one.

Keywords: 3D position measurement, rotating scanning mechanism, Fresnel diffraction pattern, light intensity modulation, linear-period modulation.

1. INTRODUCTION

A large-scale highly accurate two dimensional (2D) digitizing system with a cordless cursor has been developed, using laser-ray and rotating mirror [1]. The average accuracy of 2 m×6 m and 3 m×4m systems is within ±0.15 mm. This system can be applied to plane surveying field [2,3]. The average accuracy for an indoors area of 30 m×30 m is about ±5.5 mm. Our efforts have the goal of expanding such systems to three dimensions (3D).

Since a 3D digitizing system is also demanded by many fields, we seek an effective method to realize the system in a wide range of applications. When considering 3D optical measurement, countering the influence of background light is critical, because it is a serious source of measurement noise and error. Especially in a passive system that uses a charge coupled device (CCD) camera to show the position of the target, determining the center of gravity of the observed image is typically used to remove the above mentioned influence. However, it is difficult to search for the exact center position, as it depends upon the form and state of an observed image on a CCD camera, and so highly precise measurement becomes difficult.

In our research, we propose using the technology of light intensity modulation [4-6] to avoid the influence of background light. In light intensity modulation, the intensity of a light-emitting diode (LED) attached to the head of a cursor is suitably modulated with a specific waveform, and the resulting light pattern is projected onto a CCD camera by rotating scanning mechanism.

Then, the correlation between the observed pattern on CCD camera and the modulated pattern of light intensity suppresses the influences of back ground light distributions, thus enabling the position of the cursor (in CCD camera coordinates) to be measured with sub-pixel resolution.

Thus, in this paper we propose the basic principle of a new image measurement that avoids the effect of the background light by the use of the rotating scanning mechanism and light intensity modulation technique, along with a fundamental experiment. In light of the desirability of compactness and portability, we also describe 3D cursor position measurement using a monocular optical system using a linear-

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period modulated (LPM) waveform as the light-modulating one and its numerical experiment that verifies the possibility of realizing the above monocular system.

2. 3D DIGITIZING SYSTEM BASED ON TRIANGLATION [7]

Fig. 1 shows the configuration of the proposed system for measuring the position of a target in 3D space. Having a LED attached on its head, the target (shown as the "Cursor" in the Fig. 1) plays the role of a digitizing cursor. The system is composed of two optical units to measure the 3D position of the cursor. Each optical unit includes a rotating plane mirror (RM) and a CCD camera, as shown in the Fig. 1.

The rotating mirror scans the light emitted by the LED on the target, and projects it onto the image plane of the CCD camera. If the light intensity of the LED is modulated according to a specific function, a similar pattern to the modulating function is observed along scanning lines of the CCD image plane. If the light modulating function has wide-band frequency components, the correlation between the modulating function and observed video signals will provide a high signal to noise (S/N) ratio and enable us to detect the

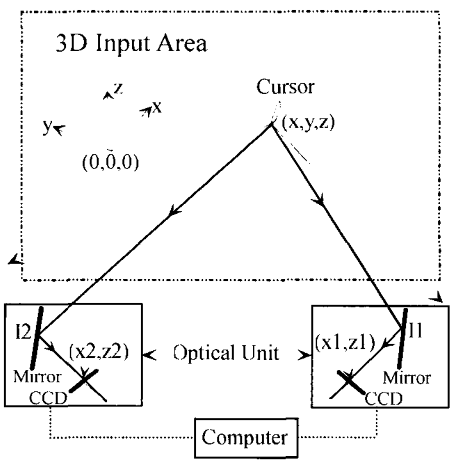

Fig. 1. System configuration for measuring a target in 3D space through triangulation.

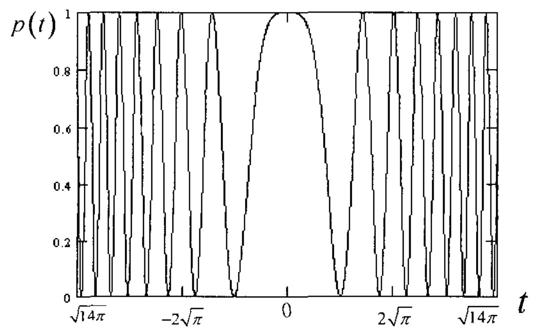

Fig. 2. An example of Fresnel pattern.

emitted light pattern otherwise contaminated by strong background-light noise. Accordingly, we designed the following function for the intensity modulation of the light emitted from the LED [1]:

$$p(t) = \left(1 + \cos t^2\right)/2, \quad (1)$$

where the frequency of this function increases linearly with time, and is known as Fresnel's diffraction function (this example is shown by Fig. 2).

Here, the RM and CCD camera which especially play an important role on our measuring method are assumed as follows:

(a) Rotating plane mirror with constant speed (RM)

The rotating speed of the RM is chosen such that the image moves over about one half of the entire picture frame within the frame time (about 1/60 seconds) of the CCD and is kept constant synchronized with the system clock.

(b) CCD camera

This sensor sends out the integrated value of the incident amount of light within one frame time. The phase relationship of the synchronization is chosen such that the RM is oriented to the direction to capture the entire observation region into the CCD camera at the center time of the intensity-modulated waveform of LED.

One example of experiment parameter is

(a) LED: Ultra high brightness LED lamp (Peak wavelength=627 nm, 18500 mcd/IF =20mA).

(b) CCD camera: High sensitivity analogue camera (512 pixels× 521 pixels).

(c) RM: Plane mirror which is installed in Brushless DC Motor whose rotating speed is 600 rpm.

(d) Light intensity modulation

Light intensity waveform is divided into 4096 on the time axis and its frequency is 0.5 MHz.

In our experiment, an one second or more is required in our correlation calculation. But, it can be calculated sufficiently possible within one second by improving each part of optical system. And, if this system is used at wide measurement area, high resolvable camera is naturally needed. The pixel pitch of CCD camera limits the resolvable 3D depth.

2.1. Determination of the cursor displacement in the CCD image plane

Let's consider the rectangular coordinates x and z in the image plane, and let x be extending along the horizontal scanning direction of the CCD camera. Putting the cursor initially at the center point in 3D measuring area, we observe a projected light pattern on the CCD image plane.

We designate this pattern by $F(x_m, z_n)$ and call it the "reference" image. In this notation, both m and n denote the pixel position along the horizontal and the vertical direction, respectively. The displacement of the center of the Reference image from the origin of the image coordinates is expressed as $(\delta x_0, \delta z_0)$ and is measured by correlation operation.

When the cursor leaves the center point in the measuring area, the projected light pattern also moves to a different position in the image plane. We call this pattern a target image and denote it by $G(x_m, z_n)$. Accumulating the intensity distribution along horizontal scanning lines, we obtain the following functions of one-dimensional intensity distribution:

$$h_R(n) = \sum_{m=1}^{M} F(x_m, z_n) \ , \qquad (2)$$

$$h_T(n) = \sum_{m=1}^{M} G(x_m, z_n) \ , \qquad (3)$$

where the suffix R and T denote "Reference" and "Target", respectively. M and N denote the number of pixels in the horizontal and the vertical directions, respectively.

We define the z coordinates at which each of the above equations has the maximum value by z_R and z_T: these values indicate the vertical position of the cursor. Accordingly, the vertical displacement of the Target from the Reference can be calculated by

$$dz = z_T - z_R \ . \qquad (4)$$

To determine the horizontal displacement of the cursor, we calculate the following cross correlation between the horizontal intensity distributions by z_T and z_R:

$$q(k) = \sum_{m=1}^{M} G(x_m, z_T) \cdot F(x_{m+k}, z_R) \ . \qquad (5)$$

The horizontal position, dx, where $q(x)$ has its maximum value, indicates the horizontal displacement of the Target from the Reference. Consequently, the cursor position in the CCD image plane can be determined as follows:

$$(x, z) = (dx + \delta x_0, dz + \delta z_0) \ . \qquad (6)$$

2.2. Evaluation of the S/N ratio improvement by light intensity modulation

As is mentioned before, the fundamental topic to make the present system usable in a non-prepared environment is to remove the effect of the objects other than the illuminating light and the cursor (background noise). Hence, it is studied based on the observation model

$$H(x,z) = h(x,z) + n_1(x,z) + n_2(x,z) \ , \qquad (7)$$

how the measurement accuracy can be improved by the rotating scan of the RM and the light intensity modulation. Here, $H(x,z)$ is the observed image, $h(x,z)$ is the output image, $n_1(x,z)$ is the background noise, and $n_2(x,z)$ is the pixel noise. And the dc component and high frequency elements (which are considered to be noise) of the above Reference image $F(x,z)$ is assumed to be eliminated by carrying out Fourier transformation. That is, $F(x,z)$ is assumed to be able to be approximated to the output image which corresponds to the intensity modulated pattern $k(p(t)-1/2)$ (k is a constant number.) as is mentioned before.

(a) Background noise $n_1(x,z)$

The stationary background pattern is changed by the rotating scan of the RM to the noise component which spatial frequency component is almost only dc component in the horizontal direction. Since the dc response in Reference image $F(x,z)$ used for the correlation process is eliminated, most of the background noise $n_1(x,z)$ can be eliminated.

(b) Pixel noise $n_2(x,z)$

From the above discussions, it is considered that the dc component is eliminated from output image $g(x,z)$. Since the pixel noise $n_2(x,z)$ is white noise, the matched filter theory can be applied directly.
For any Target image $G(x,z) = g(x,z) + n_2(x,z)$, $H(x,z) = k' g(x,z)$ is the function maximizing the S/N ratio of $\int H(x,z) g(x,z) dx$ to $\int H(x,z) n_2(x,z) dx$. For Reference image $F(x,z)$, $F(x,z) \cong k'' g(x,z)$ can be approximately satisfied. Hence

$$F(x,z) \cong k''' g(x,z) \qquad (8)$$

is approximately established (k', k'' and k''' are constant numbers).

Therefore, when the image plane coordinate of the cursor LED is derived by the correlation process, the effect of the pixel noise $n_2(x,z)$ is considered to be suppressed in the almost optimum form.

2.3. Preliminary experiments and results

In order to prove the feasibility of the proposed method, we performed a preliminary experiment (Fig. 3 shows the fundamental experimental system which is used by this experiment.) through the following procedure by using only one optical unit:

(a) Observe the reference image by locating the cursor initially.

(b) Observe a target image by moving the cursor at

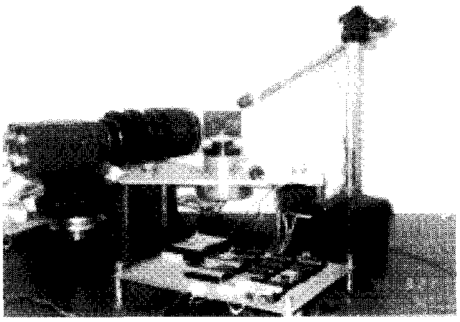

Fig. 3. Fundamental experimental.

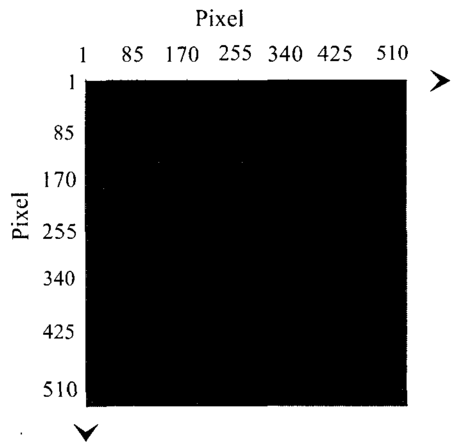

Fig. 4. A typical example of the Reference image.

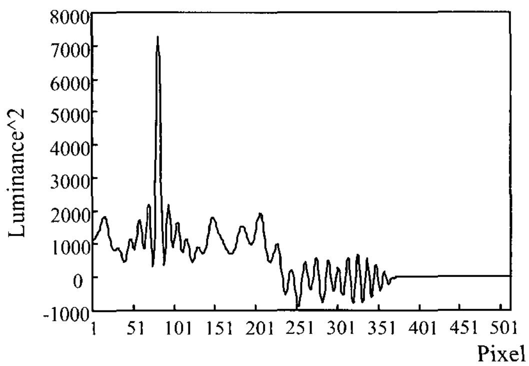

Fig. 5. Cross correlation between the Reference and a Target image at the case of darkroom.

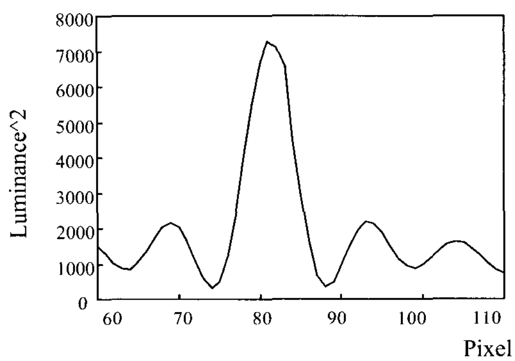

Fig. 6. Center part of the cross correlation between the Reference and a Target image at the case of a darkroom.

a short distance from the initial position.

(c) Calculate the cross correlation function between Reference at zR and the Target at z_T.

We carried out the experiment both in a darkroom and in an ordinary room with some fluorescent tubes. Fig. 4 shows the Reference image on CCD camera observed in the darkroom. The cross correlation between the Reference and a Target shown in Fig. 5 and Fig. 6 yields a good S/N ratio to overcome the influence of background-light distributions.

By measuring the position of maximum correlation with some sort of interpolation technique, we can obtain the displacement in CCD camera coordinates of the cursor from the initial point with sub-pixel resolution. Consequently, 3D position of the cursor can be measured precisely through triangulation with two optical units.

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3. MONOCULAR SYTEM USING LINIEAR-PERIOD MODULATED SIGNAL [8]

The digitizing system described in the previous section requires two optical units in order to determine the cursor position in 3D space. However, it is highly desirable to make the system compact for realizing its portability. In this section, we describe the principle for measuring the 3D position of a cursor with a monocular optical system.

If the cursor leaves the initial point, a target image is observed in a different size compared with the reference. Thus, we can estimate the distance of the cursor from the initial point by measuring the size of the Target image on the CCD image plane.

It is therefore advisable to design the light modulation function so that we can measure the size alteration caused by the cursor displacement

We, therefore, propose the use of a linear-period modulated (LPM) signal [9,10] as the temporal function to modulate the LED intensity whose example is shown by Fig. 7. A LPM signal is designed as follows:

$$P(t) = u_r(t) + ju_i(t), \quad (9)$$

where

$$u_r(t) = a(|t|) \cdot \cos(\Omega \log|t|) + c, \quad (10)$$

$$u_i(t) = a(|t|) \cdot \sin(\Omega \log|t|) + c, \quad (11)$$

a(|t|) denotes the amplitude function, c is the average luminance, and Ω is a parameter to determine the measurable range of the size alteration.

3.1. Basic principle for depth measurement

To observe the Reference image, we emit the LPM signal at two times. First, the real part of (10) is emitted, and next, the imaginary part (11). These observed images are denoted by $F_r(X)$ and $F_i(X)$ corresponding to the emitted component, where $X=(x_m, z_n)$.

In case of observing a Target image, we emit only the real part component. If the cursor moves toward the depth direction, then the size of the Target image alters accordingly. The Target image $G(X)$ can be expressed by $F_r(s\{X-X_0\})$, where s is a dilation coefficient of the size alteration, and X_0 is the 2D displacement in the image plane. Since X_0 can be measured in the same way as described in the previous section, we explain how to measure the dilation coefficient s.

Let the y-axis be in the depth direction, and let Y_C denote the y coordinate of the rotating center of the mirror. Let the y coordinate of the cursor at the initial position and after moving as Y_0 and Y_1, respectively. In the following procedure, we omit the z coordinate for the convenience of explanation.

(a) The dilation coefficient s can be approximated by the following equation [11]:

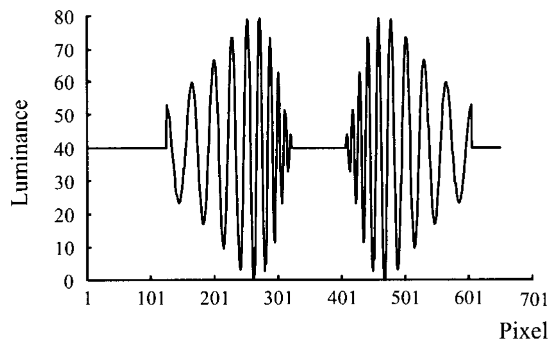

Fig. 7. An example of LPM pattern.

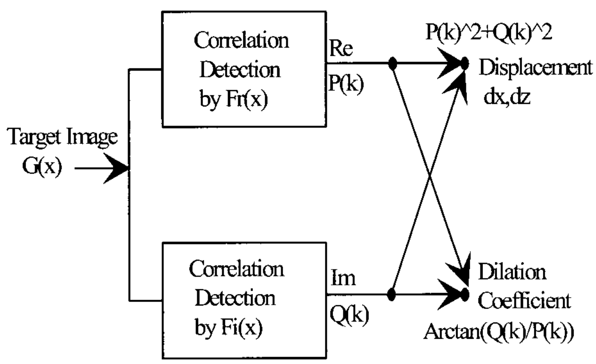

Fig. 8. Schematic diagram to measure 3D position of the cursor.

$$s \cong (1 - Y_C / Y_0)/(1 - Y_C / Y_1) . \tag{12}$$

(b) Calculating the cross correlation between the References and a Target as shown in Fig. 8, we obtain the following values:

$$P(k) = \sum_{m=1}^{M} F_r(x_m) \cdot G(x_{m+k}) , \tag{13}$$

$$Q(k) = \sum_{m=1}^{M} F_i(x_m) \cdot G(x_{m+k}) . \tag{14}$$

(c) The dilation coefficient s can be expressed by the following relationship:

$$\Omega \log s = \arctan\{Q(k)/P(k)\} . \tag{15}$$

(d) If we measure the position Y_C and Y_0 in advance, we can estimate the depth of the Target Y_1 from (12) and (15).

(e) Find the coordinate X_0 where the cross correlation has its maxim.

In Fig. 8, reference images, target image and dilation coefficient are described as the following equations:

For the reference images

$$Fr(x) = a(x)\cos\{\Omega \log(|x|)\} + c , \tag{16}$$

$$Fi(x) = a(x)\sin\{\Omega \log(|x|)\} + c . \tag{17}$$

For the target image

$$G(x) = Fr\{s(x - dx)\} . \tag{18}$$

And for the dilation coefficient

$$s = (1 - Y_C / Y_0)/(1 - Y_C / Y_1) . \tag{19}$$

Finally, we obtain the 3D displacement (dX,dY,dZ) of the cursor from the initial point by the following equations:

$$\begin{pmatrix} dX \\ dY \\ dZ \end{pmatrix} = \begin{pmatrix} (c_1 - c_0) \cdot \delta x + c_1 \cdot dx \\ Y_1 - Y_0 \\ (c_1 - c_0) \cdot \delta z + c_1 \cdot dz \end{pmatrix} , \tag{20}$$

$$Y_1 = \frac{s \cdot Y_C Y_0}{Y_0 (s-1) + Y_C} , \tag{21}$$

$$c_0 = \frac{Y_0}{f} , \quad c_1 = \frac{Y_1}{f} \tag{22}$$

where f is the focal length of the CCD camera.

3.2. Numerical experiment and result

In order to verify the validity of the measurement principle described above, we performed a numerical experiment considering the actual size of devices whose procedure is described as follows:

(a) Focal length of the CCD camera (unit: mm):
f=12.5.

(b) Rotation center of the mirror (unit: mm):
$(X_C, Y_C)=(1,100)$.

(c) Initial position of the cursor (unit: mm):
$X_0=0$, $Y_0=1500$, Z0=0.

(d) Amplitude of the LPM signal observed on the CCD camera (unit: pixel):
a(|t|)=40.

(e) Average luminance (unit: pixel):
c=40.

(g) Measurable range for the size alteration:
$s_{max} = 1.1$.

(h) Chirp rate of the LPM signal:
$\Omega = \pi/\log(s_{max})$,
center frequency is 0.05 cycle/pixel, situated frequency band length is 0.07 cycle/pixel with containing 2.5 % uniform error at each pixel which pattern exists.

(i) Measurable area (unit: mm):
-300 <= X <= 300, 600 <= Y <= 1600,
-200 <= Z <= 200.

Table 1 shows the result of the numerical experiment vs. the cursor position Y_1: the error of the size alteration E(|ds|), and the error of the cursor position $E(Y_1)$. The size alteration can be estimated precisely and the depth measurement is achievable in an accuracy of less than 3 mm in the range from 600 mm to 1600 mm. The result of the numerical experiment shows the possibility of realizing 3D digitizing system with a monocular optical unit.

4. CONCLUSIONS

In this paper, a fundamental investigation is carried out in a 3D semi-passive digitizing system using light intensity modulation. The basic principle of a new image measurement that avoids the effect of the background light by the use of the rotating scanning mechanism and light intensity modulation technique and its fundamental experiment are described. As a result of experiment, it is found that the present measurement method is less likely to be affected by the light from the surrounding objects and can realize resolutions smaller than a single pixel. Therefore, a high precision in 3D digitizing system is expected to be realized.

Since it is highly desirable to make the system compact for realizing its portability, we investigate the measuring the 3D position of a cursor with a monocular optical system using a LPM waveform as the light-modulating one. As a result of numerical experiment, the possibility of realizing the 3D digitizer with a monocular optical system is verified.

We have also been researching and developing a large-scale interferometer system for measuring silicon wafer whose size is ϕ 400 mm. One of the serious problem is the countermeasure of environment, for example, air turbulence and vibration of system or so to realize high accuracy with nano-order except that of systematic errors [12]. We think that the method using light intensity modulation proposed in this paper may also be effective to suppress the above environmental influence by using a suitable intensity modulation of light source.

Table 1. Relation between s, Y_1 ,E(|ds|) and δ (ds) ($*10^{-8}$) ,$E(Y_1)$,δ (Y_1).

s	Y_1	E(|ds|)	δ_{ds}^2	$E(Y_1)$	δ_{Y1}^2
0.9956	1600.04	0.000123	1.54	2.97	3.04
1.0000	1500.00	0.000131	1.64	2.74	3.42
1.0117	1291.48	0.000141	1.76	2.15	2.69
1.0175	1208.90	0.000128	1.59	1.68	2.10
1.0233	1137.03	0.000151	1.92	1.74	2.22
1.0350	1018.02	0.000133	1.62	1.20	1.47
1.0467	923.52	0.000148	1.83	1.07	1.33
1.0583	846.66	0.000156	1.91	0.93	1.14
1.0758	754.96	0.000141	1.76	0.65	0.81
1.0933	683.32	0.000157	1.96	0.57	0.72
1.1108	625.81	0.000149	1.88	0.56	0.56

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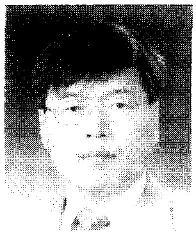

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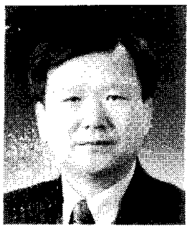

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