Basic Examination on 3D Measuring System Using Pulse-Compression

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In this paper, we propose the basic measurement method of a 3D digitizer using a CCD camera in detail. In the localization measurement with a CCD camera, the effect of the background light and the sensitivity consideration are always problems in realizing a high precision. In this research, a new measurement principle is proposed in which the pulse compression technique known in radar is used to eliminate the effect of background light even under a low intensity light source, and the coordinate values on the CCD camera image plane are determined accurately. From the quantitative evaluation of the S/N ratio improvement and the fundamental experiment, it is verified that a substantial improvement in the S/N ratio is realized for both the background noise and the pixel noise and that a resolution of less than the pixel is sufficiently possible.

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1. Introduction

As the advantages of design automation are recognized in many areas such as construction, advertising, fashion and gardening, the use of digitizers has been spreading widely.[1] For coordinate detection, planar distributed devices such as magnetostrictive sheets have been used.[2] However, this principle makes it difficult to plan new applications and particularly to plan increased size and portability. In this research, a large optical two-dimensional (2D) digitizer based on the triangulation using laser beams has been developed. In order to satisfy the requirement for guaranteed accuracy in the entire measurement area, ease of calibration, enhanced portability by unitizing, and low cost, the mechanism is used in which the moving part is limited to a rotating mirror with a constant speed. Further, by designing a linearized algorithm to absorb the alignment error, an average coordinate accuracy of ±0.15mm is realized with a coordinate area 4m×3m for industrial design use.[3] As an application of the present system in the planar metrology area, a large digitizer with an average coordinate accuracy of less than 5mm within a 30m square indoor area is reduced to practice for planar metrology.[4]

Based on these accomplishments, this research studies modification of the optical 2D digitizer to a 3D form to respond to the needs of recent 3D coordinate meaurements.[5, 6] From the understanding that the most significant contribution to high accuracy and low cost of the 2D digitizer lies in the transformation measurement from the angle to the time by a rotating mirror, the use of a similar mechanism is considered for a 3D digitizer. Under this presumption, the most natural method for 3D realization is an active method in which the laser beam is transformed into three sheet beams and the 3D information is obtained from the angles of the returning beams. However, since the amount of light returning after reflection at the cursor becomes weaker in an inversely proportional manner to the distance, the system has not been reduced to practice due to contradiction of increasing the size and damage made by the high intensity laser.

In the present research, this problem is considered to be fundamental along with the realization of 3D. New systems have been sought for a 3D digitizer less likely to be affected by the external noise(other illumination and objects except cursors) even under a weak light source.[7] A CCD image sensor (CCD) preceded by a constant rotating mirror and a light emitting diode (LED) with time modulation are used as the fundamental building blocks. An application of the pulse compression technique[8] which is well known in radar is attempted. In the pulse compression technique, the high power pulses are realized and the effect of the external noise is suppressed by sending pulses with a long pulse width while the transmitted peak power is kept low. Similarly, in the proposed system, the LED source is equivalently converted to a high intensity light source by the pulse compression technique so that the effect of the background light is suppressed. At the same time, the angle-time transformation measurement by a constant rotating mirror is realized on the CCD.

This paper describes the fundamental principle and the theoretical analysis of a new image measurement method that suppresses the background noise errors and the pixel errors in optimum forms by the use of the rotating scanning mechanism and the pulse compression technique in detail. We verify whether this can be achieved by a fundamental experiment.

2. System configuration

The configuration of the present system is shown in Fig. 1. In the figure, the dotted lines indicate the region covered by the light from the LED while the solid lines indicate the optical paths for image formation in the CCD camera.

The configuration and function of each unit are assumed as follows:

(1) Cursor

One fixed LED transmits an intensity-modulated beam. The sending timing of the modulated light can be determined accurately from the optical unit by using an infrared beam.

(2) Optical unit

Two optical units are fixed at two different positions from which the entire measurement space can be observed. Each unit consists of a constant rotating mirror (RM), a camera lens, a CCD, a LED for rotating angle detection, and a photo detector (PD).

(3) Constant rotating mirror (RM)

This is placed in front of the camera lens so that the image on the CCD is shifted in the direction orthogonal to the rotating axis. 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 constantly synchronized with the system clock. By the rotating angle detecting PD and LED, the pulses are generated at timings at which RM corresponds to them

(4) CCD image sensor

This sensor sends out the integrated value of the incident amount of light within one frame time. By using the above RM-aiming timing pulse, the frame initiation time of the CCD is synchronized with the modulated light sending timing and the RM rotating position.

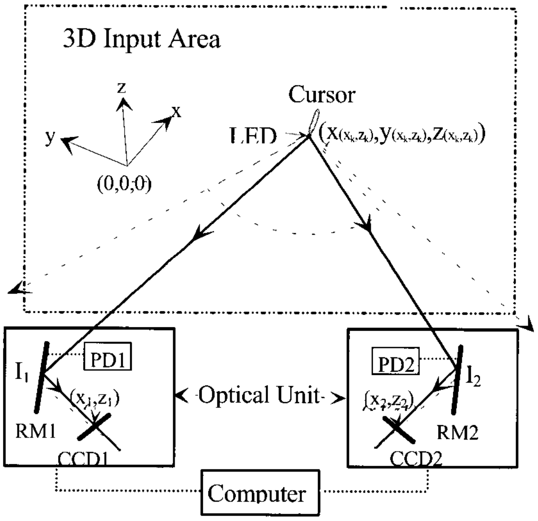

Fig. 1 System configuration for measuring a target in 3D measuring space

Accurate synchronization of the RM rotation and the LED emission is extremely important for carrying out the time-angle transformation measurement. To this end, the contribution of the high resolution of the RM-aiming pulses and the high-speed stability of the RM is significant. The phase relationship of the synchronization is chosen such that the RM is oriented in the direction to capture the entire observation region into the CCD at the center time of the intensity-modulated waveform of the LED.

3. Fundamental measurement principle

A high precision method for determination of the cursor image plane coordinate and an evaluation result of the S/N ratio improvement by the pulse compression are described.

3.1 Summary of the semi-passive measurement system using a rotating scanning mechanism

The system with an optical source installed at the cursor and a rotating scanning mechanism immediately in front of the CCD camera is called the semi-passive structure. This structure is employed in order to utilize the advantages of the 2D digitizer, namely

(a) Easiness of using a large area,

(b) Concentration of accuracy requirement into a few units,

(c) Possibility of decomposition and high portability, and

(d) High operability of measurement.

In the present configuration, it is necessary to determine 3 degrees of freedom per point in order to realize a 3D measurement. The conceivable devices as classified by the measurement degrees of freedom are as follows:

(1.1) Non-modulation of cursor light source

In the usual CCD camera measurement, the two-dimensional orientation of the cursor can be determined from the camera coordinate values. However, in order to increase the accuracy of the 3D measurement accuracy, a positional measurement accuracy of more than one pixel is needed. There is a limit in improvement of the sensitivity. Also, light generated from some sources except the cursor enters the CCD camera. By rotational scan of the field of view, the measurement degrees of freedom for a steady light source is reduced to one dimension.(See A, B 1 in Fig. 2.)

(1.2) Time modulation of cursor optical source (Part 1)

In combination with the rotating scan, the time modulated optical source is photographed as bright and dark optical bands. By a deconvolution process similar to the pulse compression technique, the equivalent amount of light is substantially increased so that the accuracy of the calculated cursor position less than one pixel and the separation from the background light are enhanced. For the modulated optical source, a 2D measurement of the degree of freedom is secured by a combination with the rotating scan of the field of view of the CCD camera. (See B 2 in Fig. 2.)

(1.3) Time modulation of cursor optical source (Part 2)

Depending on the distance between the cursor and the optical unit, the scale of the bright and dark optical bands changes on the CCD camera image. When the distance is measured from this scale change, the remaining degree of freedom can be determined. (See B 3 in Fig. 2.)

By combining the above schemes, the following formats are considered available as a measurement method of a semi-passive 3D digitizer.

(2.1) 2 CCD camera (stereo) type

In this method, the 2D coordinate values of the CCD camera image plane are derived from two directions. Based on the measured values, the cursor location is determined. As described in (1.2) above, in order to accurately derive the coordinate values of the CCD camera image plane, it is necessary to carry out a theoretical analysis and a fundamental experiment for testing the possibility of practical use of the pulse compression technique. It is indispensable to verify whether the influence of the background light can effectively be eliminated with a low intensity source.

(2.2) 1 CCD camera (monotonic) type with distance measurement capability

This type of system carries out a 3D measurement with a single optical system. This is realized by carrying out the measurement of coordinate values on the above CCD camera image plane as well as the distance measurement. Hence, in addition to verification of the pulse- compression technique in the above stereo type, it is necessary to investigate the feasibility and the selection of the optimum modulation method to secure sufficient accuracy of the distance measurement.

In this paper, the stereo method as the foundation is first discussed among the two measurement methods described above. Also, the monotonic method will be studied in the subsequent paper.

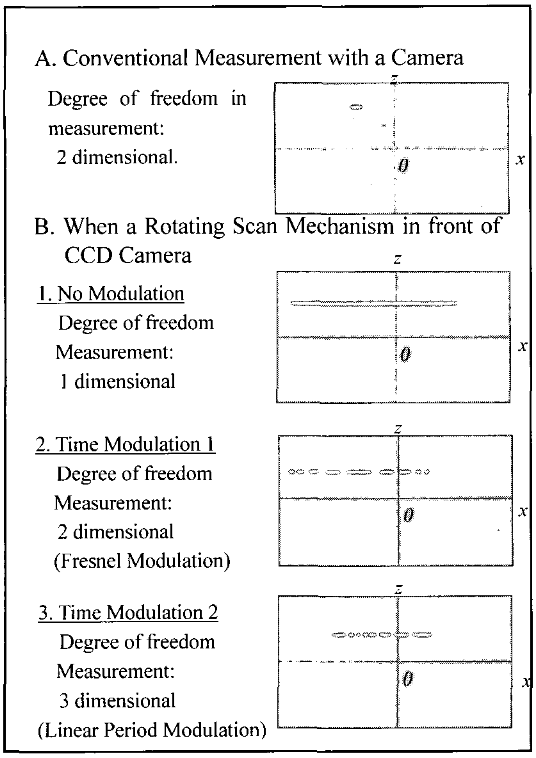

Fig. 2 The modulation of LED's brightness and the numbers of measurement

3.2 Extension of the cursor LED image by modulated light

In the system shown in Fig. 1, the CCD in each optical unit records the modulated light from the cursor as bright and dark rows sequential in the direction orthogonal to the RM rotating axis.

The coordinate system of the CCD image plane is set with the optical axis as the origin, the horizontal direction as the x-axis and the perpendicular direction as the z axis. The rotating axis of the RM is parallel to the z-axis. The intensity-modulated waveform of the LED is a Fresnel waveform superposed with a dc component.

$$p(t)=\frac{1}{2}\left\{1+\cos\left[\alpha t^2\right]\right\} \tag{1}$$

where α indicates 1/2 of the instantaneous frequency of $p(t)$.

The time origin is taken at the center of the Fresnel waveform and the brightness is set to the value proportional to the rotating speed of the RM. Under the above assumption, let the image of the LED be at the same origin $f_0^{(j)}(x,z)$. Then, in response to the horizontal shift (normalized to the pixel spacing =1) of the velocity v by the RM, the image at the time t is expressed as $p(t)f_0^{(j)}(x-vt,z)$. Hence, by the frame integration operation of the CCD, the output image is

$$\begin{aligned} f^{(j)}(x,z) &= \int_{-T/2}^{T/2} vp(t)f_0^{(j)}(x-vt,z)\,dt \\ &= \int_{-Tv/2}^{Tv/2} p\left(\frac{x_0}{v}\right)f_0^{(j)}(x-x_0,z)\,dx_0 \end{aligned} \tag{2}$$

where T is the frame time and the superscript (j) distinguishes the left or right optical units.

Since $f_0^{(j)}(x,z)$ is similar to a delta function, this is equal to the diffusion of the LED image by the Fresnel modulation pattern truncated by the width Tv. However, the propagation time of the light is neglected and the measured region is assumed to be contained within a region sufficiently close to the axis.

In practice, it is possible that the vertical components appear in v due to the distortion near the image or the spatial steadiness on the image plane may be broken. In such cases, a cross correlation process dependent on the position is carried out with the pattern obtained by placing the cursor at an appropriate position.

3.3 Determination of image plane coordinates of the cursor by pulse compression

The form of equation used for compression of the above diffusion pattern is as follows:

$$\tilde{p}\left(\frac{x}{v}\right)=\operatorname{rect}\left(\frac{x}{Tv}\right)v\cos\left(\alpha\frac{x^2}{v^2}\right) \tag{3}$$

which is obtained by removing the dc component from the modulation waveform truncated at the frame time (See Fig. 3). By taking cross correlation with the above equation, the image is changed to

$$\begin{aligned} \psi(x,z) &= \int_{-Tv/2}^{Tv/2} \tilde{p}\left(\frac{x_1}{v}\right)f^{(j)}(x+x_1,z)\,dx_1 \\ &= \int_{-Tv/2}^{Tv/2}\int_{-Tv/2}^{Tv/2} h^{(j)}(x_0,x_1)\,dx_0\,dx_1 \\ &= \int_{-Tv/2}^{Tv/2} \psi_{\tilde{p}p}\left(\frac{x_1}{v}\right)f_0^{(j)}(x_0-x_1,z_0)\,dx_1 \end{aligned} \tag{4}$$

$$\text{where } h^{(j)}(x_0,x_1)=\tilde{p}\left(\frac{x_1}{v}\right)p\left(\frac{x_0}{v}\right)f_0^{(j)}(x-x_0+x_1,z). \tag{5}$$

and $\psi_{\tilde{p}p}(x/v)$ is the correlation function between $\tilde{p}(x/v)$ and $p(x/v)$. And it is specifically approximated as

$$\begin{aligned} \psi_{\tilde{p}p}\left(\frac{x}{v}\right) &= \int_{-T/2}^{T/2} \tilde{p}\left(\frac{x_0}{v}\right)p\left(\frac{x+x_0}{v}\right)dx_0 \\ &= \frac{v^2}{8\alpha x}\left[\sin(a(x))-\sin(b(x))\right] \\ &\quad +\sum_{k=1}^{4}c_k^x\text{FresnelC}\left[b_k^x\right]+\sum_{k=1}^{2}d_k^x\text{FresnelS}\left[e_k^x\right] \\ &\cong \frac{v^2}{8\alpha x}\left[\sin(a(x))-\sin(b(x))\right] \\ &\cong \frac{Tv}{4}\sin c\left(\frac{\alpha Tx}{v}\right) \end{aligned} \tag{6}$$

where

$$a(x)=\frac{\alpha}{v^2}x^2+\frac{\alpha T}{v}x,\ b(x)=\frac{\alpha}{v^2}x^2-\frac{\alpha T}{v}x\cdot \tag{7}$$

Hence, if the peak location of the cursor LED image is (x_0,z_0), then

$$\psi(x_0,z_0)\approx\frac{Tv}{4}f_0^{(j)}(x_0,z_0). \tag{8}$$

Hence, by the correlation process, the peak of the cursor LED image is enhanced by a factor of $Tv/4$ and the correlation peak width can be estimated by the distance $\pi v/\alpha T$ to the first zero of sinc function. Here, from Nyquist condition originated from the pixels in the CCD, α needs to be selected as

$$\frac{\pi v}{\alpha T}>1 \text{ or } \alpha<\frac{\pi v}{T}. \tag{9}$$

From the image $\psi(x,z)$ obtained after the above correlation process, the image plane coordinates of the cursor LED are determined. Specifically, the peak location is derived by assigning a quadratic function to the distribution near the peak so that the coordinate values with the sub pixel accuracy are determined. In the following discussions, this is expressed as (x_k,z_k).

3.4 Evaluation of the S/N ratio improvement by pulse compression

As mentioned in Introduction, 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) while a low power optical source is used. Hence, it is studied based on the observation model

$$g^{(j)}(x,z)=f^{(j)}(x,z)+n_1^{(j)}(x,z)+n_2^{(j)}(x,z) \tag{10}$$

to investigate how the measurement accuracy can be improved by the rotating scan of the RM and the pulse compression.[11]
Here, $f^{(j)}(x,z)$ is the observed image, $n_1^{(j)}(x,z)$ is the background noise, and $n_2^{(j)}(x,z)$ is the pixel noise.

3.4.1 Background noise $n_1^{(j)}(x,z)$

If the stationary background pattern is $f_b^{(j)}(x,z)$, this is changed by the rotating scan of the RM to the noise component given by

$$n_1^{(j)}(x,z)=\int_{-T/2}^{T/2} f_b^{(j)}(x-vt,z)dt. \tag{11}$$

Since this indicates the image of the background pattern blurred by the width of Tv, only the spatial frequency components close to dc are left over in the horizontal direction. However, since the dc response in Eq. (3) used for the correlation process is eliminated, most of the above are eliminated. Hence, a double S/N ratio improvement effect is expected in the sense that the rotating scan of the RM and compression act as a high and low cut filter for the stationary scene and as a sharp compression enhancing filter for the modulated LED image.

3.4.2 Pixel noise $n_2^{(j)}(x,z)$

First, from the above discussions, it is considered that the dc component is eliminated from $f^{(j)}(x,z)$.
Since the pixel noise $n_2^{(j)}(x,z)$ is white noise, the matched filter theory can be applied directly.
For the signal $g^{(j)}(x,z)=f^{(j)}(x,z)+n_2^{(j)}(x,z)$,
$h^{(j)}(x,z)=k'f^{(j)}(x,z)$ is the function maximizing the S/N ratio of

$$\int h^{(j)}(x,z)f^{(j)}(x,z)dx$$

to

$$\int h^{(j)}(x,z)n_2^{(j)}(x,z)dx.$$

Hence,

$$\frac{\left|\int h^{(j)}(x,z)f^{(j)}(x,z)dx\right|^2}{E\left[\left|\int h^{(j)}(x,z)n_2^{(j)}(x,z)dx\right|^2\right]}\le\frac{\int\left|f^{(j)}(x,z)\right|^2 dx}{\sigma^2} \tag{12}$$

where the equality holds when $h^{(j)}(x,z)=k'f^{(j)}(x,z)$ (k' is a constant while $\sigma^2\delta(x,z)$ is the auto-correlation function value of $n_2^{(j)}(x,z)$). It is found from Eq. (3) that the function $\tilde{p}(x/v)$ used for correlation process clearly satisfies

$$h(x,z)\cong k''\tilde{p}\left(\frac{x}{v}\right) \quad (k'' \text{ is an arbitrary constant}). \tag{13}$$

4. Fundamental experiment and results

The method of determination of the coordinate values described above has problems in that the accurate derivation of the moving velocity v of the image is not easy and that the calculation of the two-dimensional correlation function requires time. Hence, in practice, an arbitrary position of the cursor with respect to an appropriate reference point is accurately derived in the form of a 2D displacement on the image plane, especially the horizontal displacement by eliminating the effect of background light. This is verified in the fundamental experiment. In order to make clear the pulse compression effect, the dc component is eliminated for the reference image as in Eq. (3).

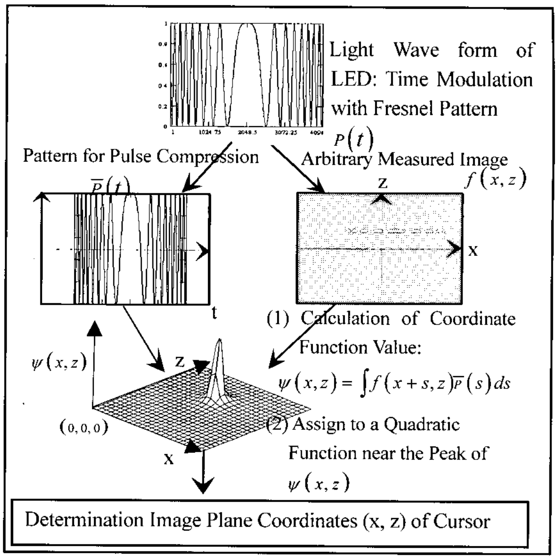

Fig. 3 Highly accurate determination of the cursor displacement in the CCD image plane by Pulse-Compression technology

4.1 Experimental method

As the light emitting waveform of the LED, the Fresnel pattern in Fig. 4 is used. This waveform is divided in $2^{12}(=4096)$ intervals on the time axis.

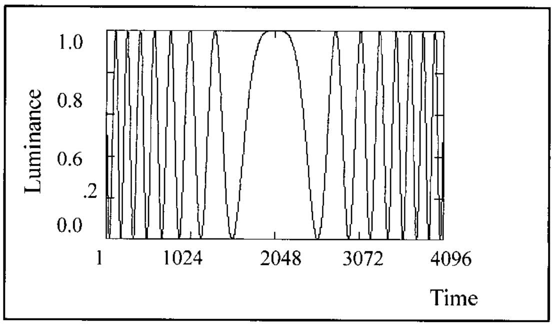

Fig. 4 Fresnel pattern used by experiment

The LED is placed at about 80cm in front of the RM. Measurement is carried out in both a dark room and a general room with usual fluorescent lamps and the sharpness of the peak of the correlation function are compared. Fig. 5 shows the photograph of the experimental equipment. Especially, in order to easily realize the possibility of the present measurement system, an aspherical lens with an extremely small aberration is used in the lens system.

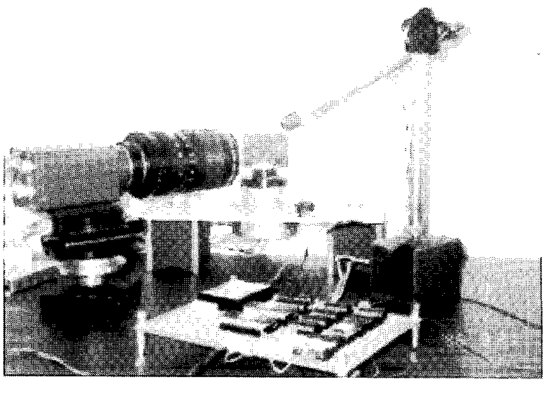

Fig. 5 Overview of the experimental system

4.2 Experiment in a dark room

Experiment is carried out in a dark room with little disturbance. First, without emitting light from the LED, the extent of the background noise is studied. It is found that the brightness detected by a CCD camera is 1 to 2 (The brightness is expressed into 256 steps from 0 to 255). Next, the LED is set in the direction toward the RM and the image waveform is acquired by the CCD camera for the emitted Fresnel waveform. In one example of the image waveform that the Fresnel waveform detected over 290 pixels in the horizontal direction, Fig. 6 expresses $h(z_k)(k=1,2,......,512)$ in the Eq. (14) below from the detected image.

$$h(z_k) = \sum_{l=1}^{512} \psi(x_l, z_k) \tag{14}$$

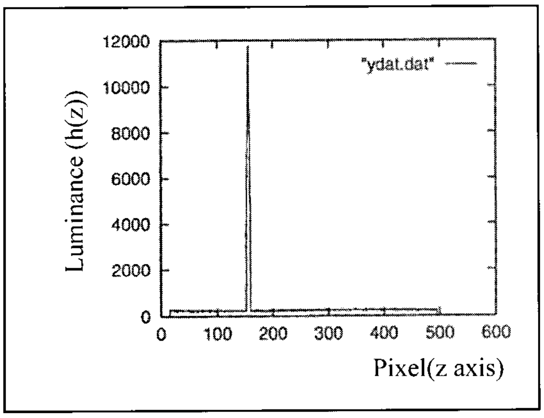

Fig. 6 The sum of each pixel of the horizontal direction at the case of the dark room

The value obtained from this image by interpolation similar to the above is $z_e = 165.3$. Next, Fig. 7 shows the brightness at each pixel in the horizontal direction at $z = 165$. Since the rays from the LED have usually some thickness on the CCD pixels, the waveforms around particular direction are superposed so that the total sum is detected as the brightness. Therefore, the zero level of Fresnel waveform appears to be raised. In the present case, the results are affected by external disturbance up to about 20. Since the external disturbance is small in the dark room, the brightness level of the Fresnel pattern is high with respect to the error level so that the shape is well preserved.

The results of the correlation process are shown in Fig. 8. According to Fig. 9, which shows the central part, the variations near the maximum value of the correlation function can be seen to be drastic. Hence, it is expected that the horizontal coordinate value on the cursor image plane can be derived accurately. An even higher accuracy can be derived by interpolation. In order to increase the resolution, the frequency bandwidth of the original Fresnel waveform is conceivable. However, from the relationship of the number of pixels on the CCD camera, the measurement range becomes narrower if the frequency range is made to be wider. The present fundamental experiment was kept to the confirmation that the measurement of the horizontal coordinate value can be made with a resolution of less than one pixel.

4.3 Experiment in a general room

In order to investigate the case in which the effect of the background light is taken into account, an experiment is carried out in a general room lighted with fluorescent lamps. Like the case of a dark room, the LED is not emitting light and the degree of error with only the background light is investigated. The brightness detected by the CCD camera was about 10~20. This is about 10 times the value in the dark room. The effect of the background light is extended to the entire room.

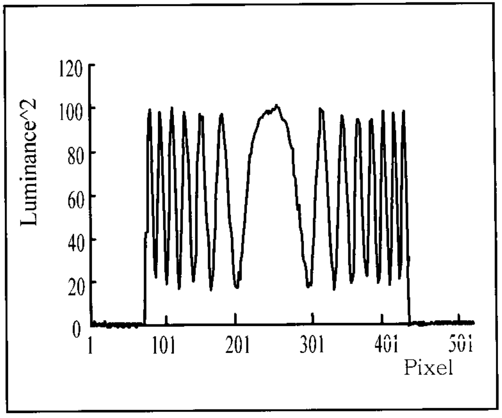

Fig. 7 Fresnel pattern detected by CCD camera at the case of the dark room

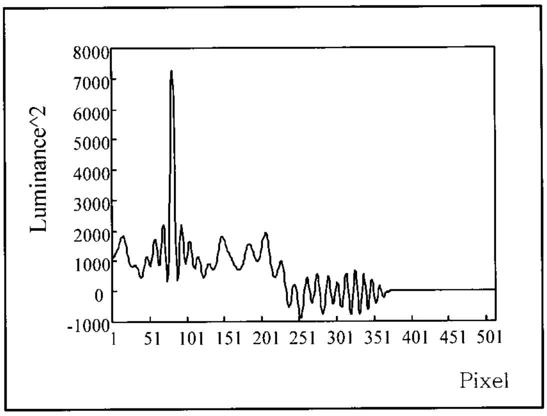

Fig. 8 Cross correlation between the Reference and a Target image at the case of the dark room

Fig. 10 shows $h(z_k)(k=1,2,......,512)$ in the present case. In comparison to the dark room case (Fig. 6), the error of the background is more significant. Especially, there is a large error factor between 50 and 100 along the y axis. This is due to the reflection of the fluorescent light by an object and illumination on the CCD image plane in a sharp bound by a high-speed rotation of the RM. Since this is always constant, it can be treated as a systematic error. The large peak between 150 and 200 from the comparison with the image data of the background is found to be the projection of the waveform from the LED.

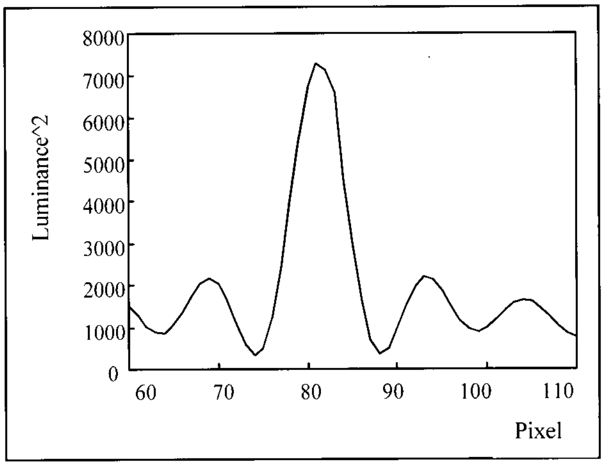

Fig. 9 Center part of the cross correlation between a Target image and a Reference image

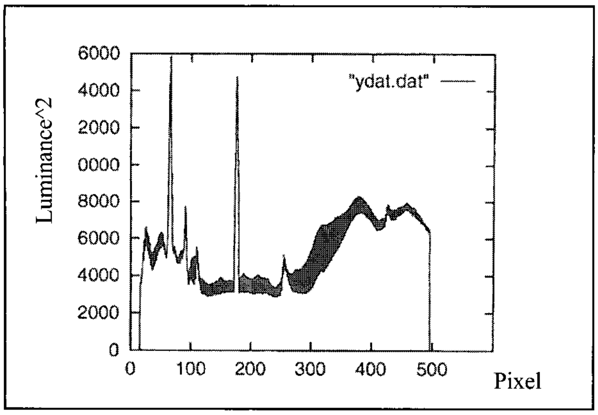

Fig. 10 The sum of each pixel of the horizontal direction at the case of the general room

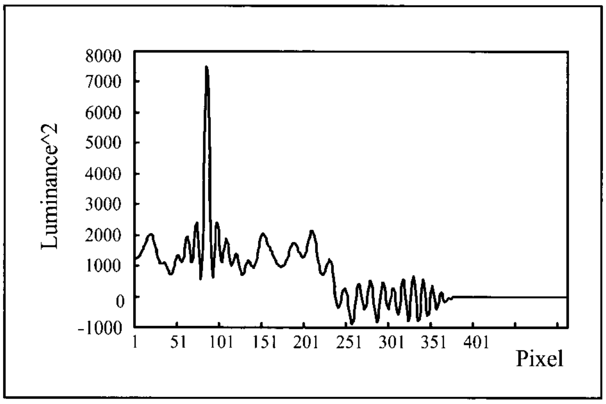

Fig. 11 Cross correlation between the Reference and a Target image at the case of the general room

Next, the results of the correlation process like the case in the dark room are shown in Fig. 11. Further, according to Fig. 12 expanding the center region, it is easily found as in the case of the dark room that the variation of the correlation function near the maximum value is drastic so the horizontal coordinate value can be derived at a resolution smaller than the pixel. In comparison to the case of the dark room, the results in the general room are shifted by about 5 pixels to the right. This indicates the setting error of the LED for the reference position and an arbitrary position in both the dark room and the general room.

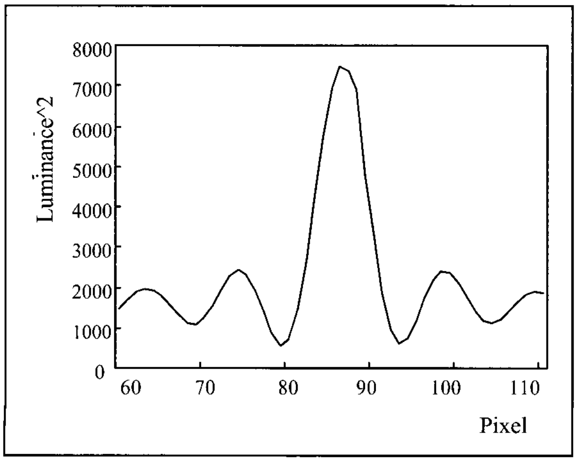

Fig. 12 Center part of the cross correlation between and the Reference and a Target image at the case of the general room

As described earlier, the brightness detected without light emitted from the LED (corresponding to the background error) is 1 to 2 in the dark room and 10 to 20 in the general room. It is considered that the error in the background is 10 times that of the dark room. It is found that there is even more background error, when the portions without peaks corresponding to the background error in Fig. 6 and Fig. 10 presenting the sum in the horizontal direction in the dark room and the general room are compared. Nevertheless, the obtained correlation functions are about the same as seen from the comparison of the figures. There is no difference in the sharpness of the peaks. Hence, the method of deriving the horizontal coordinate values of the cursor image plane by the pulse compression is verified through the fundamental experiment to have strong robustness for both the background noise and the pixel noise.

5. Conclusions

In this paper, a fundamental investigation is carried out in the 3D digitizer system of the stereo method using pulse compression. 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 the pixel. Based on the present fundamental study, it is planned to construct an actual system.

Fresnel patterns are used as the light emitting modulated waveforms. If an arbitrary position of the LED with respect to the RM is very different from the reference position, the pulse compression efficiency is degraded by the extension of the pattern projected to the CCD camera so that accurate determination of the coordinate values of the cursor on the image plane becomes impossible. This problem can be avoided by the use of a linear-periodic modulated wave (LPM wave) for which the instantaneous frequency is constant with respect to the extension ratio.[10]

As described in subsection 3.1, acquisition of the range information is expected by deriving the scale (extension ratio) of the pattern. Hence, we investigate measuring the 3D position of a cursor with a monocular optical system using a linear-period modulated (LPM) waveform as the light-modulating one. As a result of numerical experiment, it is verified that the feasibility of the 3D digitizer with a monocular optical system is possible.[11]

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

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