Measurement of 3-D Range-Image of Object Diagonally Moving against Semiconductor Laser Light Beam

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Abstract Recently, we proposed a 3-D range-image measuring system for a slowly moving object by mechanically scanning a laser light beam emitted from a self mixing laser diode. In this paper, we introduced that every object moves along a straight line course, which is set diagonally against the semiconductor laser beam so that we can recognize each shape and size parameters of objects separately from the acquired 3-D range-image.

We measured a square mesa on a square plane as an object. The measured velocity was 4.44mm/s and 4.63mm/s with an error of 0.56mm/s to 0.37mm/s. And thickness error of the mesa was 0.5mm to 0.6mm, which was obtained from the 3-D range-image of the standstill or moving object with thickness of 17.0mm.

Keywords 3-D, range-image, laser diode, self-mixing, light beam, scanning, moving object, diagonal, mesa

1. INTRODUCTION

Recently, we proposed a 3-D range-image measuring system[1] for a slowly moving object by mechanically scanning a laser light beam emitted from a self mixing laser diode (SM-LD).

In the previous system, the 3-D range-image of an object slowly moving directly against the semiconductor laser beam was acquired. In that method, the measuring time to acquire a range-image of a moving object was about 3.5 seconds, when the object was scanned with 121 (=11 x 11) points. When we have some objects to be measured, which are moving in line on a belt conveyer, we could not acquire the 3-D range image one after another by that system.

In this paper, we introduced that every object moves along a straight line course, which is set diagonally against the semiconductor laser beam. If we set more than two objects at regular intervals in line, it becomes possible to acquire the range-image of each moving object one after another. Thus, we can recognize each shape of objects separately. Also, from the acquired 3-D range-image of a moving object, we can obtain size parameters of each object.

We measured a square mesa on a square plane. We successfully acquired the 3-D range-image of the moving or stationary object. And from these 3-D range-images, we acquired size parameters and velocity of the object.

In this system, we can acquire the 3-D range-image of a moving object observed not only from the optical axis but from a point in front of the object.

2. PRINCIPLE[1-3]

2.1 3-D Image Measuring System

A schematic configuration of a 3-D image measuring system utilizing a laser diode range-finding speedometer is shown in Fig.1. The light beam emitted from an FM modulated laser diode (LD) with a continuous triangular current is scanned in 2-dimensional plane by each stepping motor. A target object under measurement is carried at a constant velocity by a linear rotary unit. The velocity direction of the moving object was set diagonally against the optical axis (z-axis) of the light beam.

2.2 Principle of Range-Finding Speedometer

The light backscattered from the object returns into the LD causing external cavity mode hops, which produce some successive discontinuities in the output of a photodiode (PD). The waveform of the output signal from the PD is shown in Fig.2 (a). By measuring the mode hop time interval, both the absolute distance L_T to the object along the optical path and the axial component V_T of object velocity are obtained simultaneously from the following equations.

$$L_T = \frac{cT}{4\Delta F_e i_m T_M} \quad (1)$$

$$V_T = \frac{\lambda}{4}\left(\frac{N_2}{T_2} - \frac{N_1}{T_1}\right) \quad (2)$$

$$\frac{1}{T_M} = \frac{1}{2}\left(\frac{N_2}{T_2} + \frac{N_1}{T_1}\right) \quad (3)$$

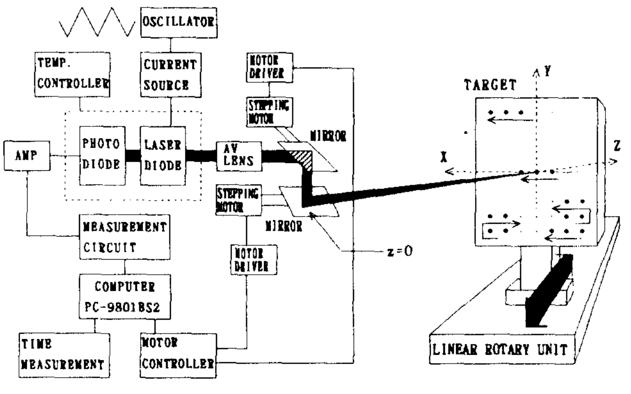


Fig.1 Schematic configuration of 3-D range image measurement system.

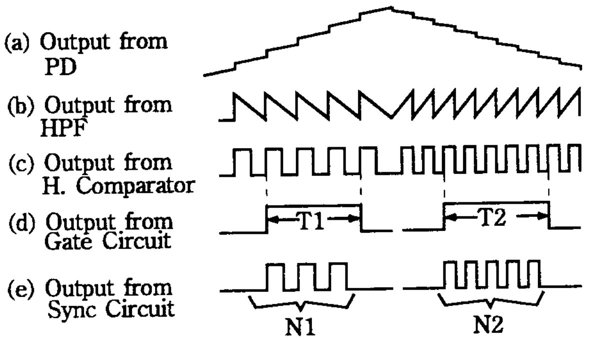


Fig.2 Principle and measurement method of range and velocity.

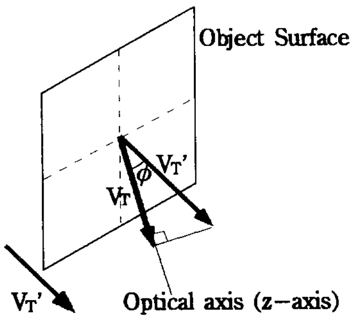


Fig.3 Velocity transform.

where c is the light velocity, T is the period of the triangular modulation current, ΔF_e is the effective modulation efficiency, i_m is the peak to peak amplitude of the modulation current, T_M is the mean mode hop time interval and λ is the light wavelength. The gate duration time T_1 and T_2 measured during the gate pulse, respectively, are shown in Fig.2.

When the measured object moves diagonally against the optical axis, the moving velocity V_T' is given by the following equation with reference to Fig.3,

$$V_T' = \frac{V_T}{\cos\phi} \tag{4}$$

where ϕ is the angle between the optical axis and the velocity vector V_T', and V_T is the object velocity observed by the light beam.

2.3 Principle of 3-D Range Image Measurement

The origin of the x-y-z coordinate system of the 3-D image measuring system is chosen at the center of the mirror for scanning in y direction. The positive direction of the z-axis is in the direction toward which the light beam starts from the origin. In this system, the positive direction of the z'-axis is in the direction toward which the moving object departs from the same origin. The coordinates of a reflecting point P(x,y,z) on a moving object are determined from the measured total length along the beam path and the known mirror angles.

In this system, one laser beam is successively scanned to obtain each data of range and velocity corresponding to each beam direction. During the acquisition of the range-image, the z value of the successively measured points increases in accordance with the shift of the object. Provided that both the time of measuring instance and the velocity for all points are known, we can reconstruct a range image of the real object, which exists at the final measuring time.

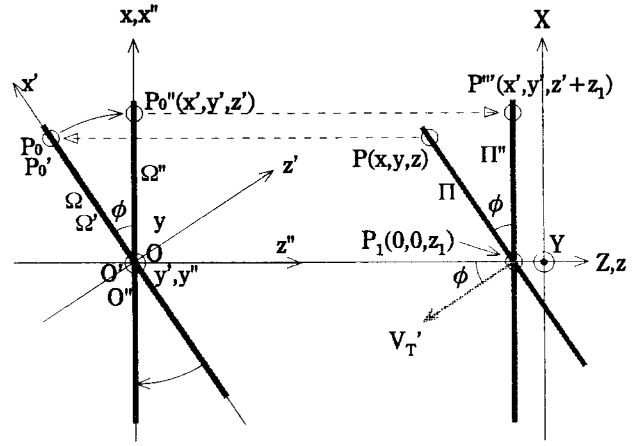


Fig.4 Coordinates transform, rotation of coordinate axes and translation of a reference plane Π.

2.4 Reconstructed Image

Figure 4 shows a schematic diagram for coordinates transform, rotation of coordinate axes and translation of a reference plane.

The coordinates of all the measured points of an object which moves in the diagonal direction against the laser light beam are expressed using the O-x-y-z coordinate system in which the optical axis is defined as z-axis. The y-axis is perpendicular to the manuscript surface. The angle between the optical axis (z-axis) and the moving direction of object is defined as ϕ. The O'-x'-y'-z' coordinate system has the same origin O, and y'-axis coincides with y-axis. The z'-axis is parallel with the moving velocity vector V_T'.

A reference plane Π which is parallel with the x'-y' plane is introduced in the region of the object. The plane Π is expressed by a file in Fig.4, and it crosses the z-axis at a point $P_1(0,0,z_1)$. A general measured point P(x,y,z) is conveniently shown on the file Π. We translate the file Π to the x'-axis and rename it as Ω and Ω' in the O-x-y-z and O'-x'-y'-z' coordinate system, respectively. We rotate both the O'-x'-y'-z' system and the Ω' around the origin O as shown in Fig.4, and we rename each of them as O"-x"-y"-z" system and file Ω", respectively. Finally, we translate back the file Ω" to the file Π". Owing to the above process, the measured point P(x,y,z) is transformed to $P'''(x',y',z'+z_1)$ through $P_0(x,y,z-z_1)$, $P_0'(x',y',z')$, and $P_0''(x',y',z')$.

In this method, the y-component of the measured point P is maintained constant through the process. So, we can discuss on the x-z or the x'-z' plane. The process is expressed as follows,

$$\begin{pmatrix} x' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} x \\ z - z_1 \end{pmatrix} \tag{5}$$

$$y' = y \tag{6}$$

$$x'' = x', \quad y'' = y', \quad z'' = z' \tag{7}$$

$$x''' = x', \quad y''' = y', \quad z''' = z' + z_1 \tag{8}$$

The measured points P(x,y,z) are displayed on the x-y-z coordinate system with white circles which are observed from the origin along the optical axis. Each of the white circles represents a beam spot on the moving object when it is illuminated at the instant of measuring. While the transformed points $P'''(x',y',z'+z_1)$ are displayed by corresponding lattice points to show the reconstructed range image which is observed from a point in front of the moving object. Owing to the abovementioned transform process, this range image also can be displayed on the same x-y-z coordinate system.

3. MEASUREMENT RESULTS

3.1 Operation Condition of the System

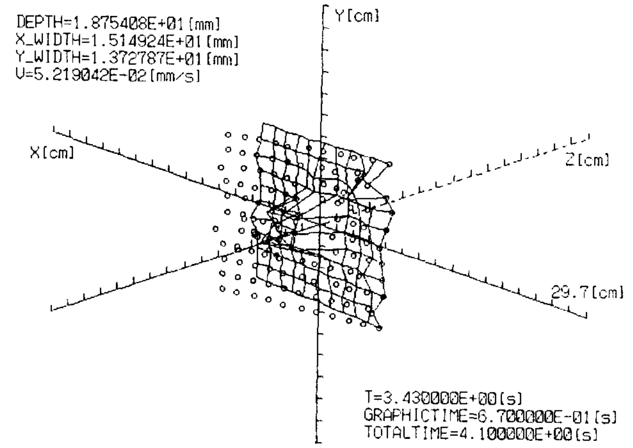
In this measurement, an AlGaAs laser diode (LTO21MF) was used. The wavelength λ was 780 nm, the output power at the second mirror was 3 mW at I=70 mA, and the focused beam spot size was about 0.2 mm. The triangular modulation frequency 1/T was 2 kHz, and the i_m was 2 $mA_{p\text{-}p}$.

3.2 Measuring Time

The measuring time of 121 points was about 3.4 seconds. And the drawing time of the range image by a computer was about 0.7 seconds. So, the total measuring time was about 4.1 seconds.

3.3 Minimum Scanning Length (MSL)

The resolution of a measured square plane placed diagonally to the light beam depends on the minimum scanning length (MSL) between the adjacent two illuminated spots on the plane. In this measurement, the MSL is about 7.6mm at the x-y parallel plane at z=30cm. At the x'-y' parallel plane at z=30cm, the MSL of the x-direction (MSLx) is about 7.8mm, and the MSL of the y-direction (MSLy) is about 7.6mm, Therefore, the minimum detectable size of a rectangular is considered as 2MSLx × 2MSLy.



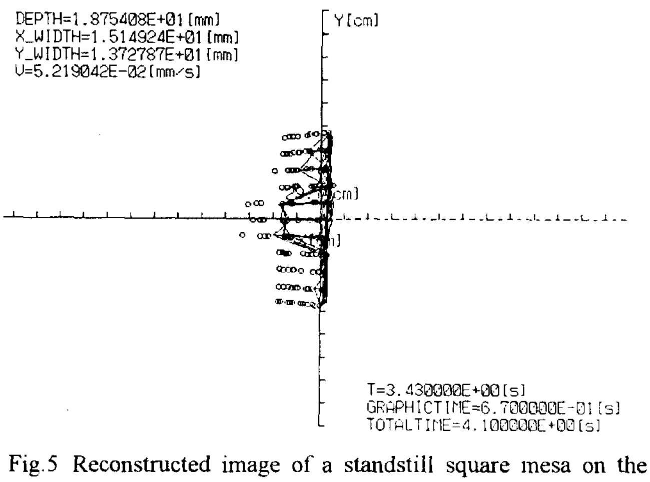


Fig.5 Reconstructed image of a standstill square mesa on the square plane.

Table 1. Measured size parameters of mesa.

		Standstill Fig.5	Depart. Fig.6	Approach. Fig.7
Width	x	15.1 mm	15.6 mm	14.8 mm
Height	y	13.7 mm	14.4 mm	13.6 mm
Thickness	z	18.5 mm	17.6 mm	17.6 mm
Size of mesa		Width and Height : 22.0 mm × 22.0 mm		
		Thickness : 18.0 mm		

Table 2. Measured moving velocity.

		Depart.	Approach.	Against
Measured	V_T	4.29mm/s	4.47mm/s	4.70mm/s
Real	V_T'	4.44mm/s	4.63mm/s	5.00mm/s
Error		0.56mm/s	0.37mm/s	0.30mm/s

3.4 Range Image of Mesa Spot

A small square mesa on a square plate which are covered with white paper was used for the measurement.

3.4.1 In Case of Standstill

Fig.5 shows a reconstructed range image of a square mesa on the square plane. The white circles represent measured points, and the solid lattice points represent reconstructed points.

Table 1 shows the measured size of the mesa. The width and height of the mesa was 22.0mm × 22.0mm, which is slightly less than 3MSLx × 3MSLy. Its thickness was 18.0mm. While the measured size of the mesa was about 15.1mm × 13.7mm in width and height, respectively, and the thickness was 18.5mm. Therefore, the thickness error was 0.5 mm, and the size error 6.9mm × 8.3mm was within the estimated error of 15.6mm × 15.2mm (2MSLx × 2MSLy).

3.4.2 In Case of Moving

Fig.6 and Fig.7 show a reconstructed image of a moving square mesa. The dimension of the mesa is 22.0mm × 22.0mm × 18.0mm. The mesa in Fig.6 is departing from mirrors and the mesa in Fig.7 is approaching to mirrors.

The measured velocity moving directly against the laser beam was 4.70mm/s.

Table 2 shows the measured velocity V_T, the corrected real velocity V_T', and measured velocity error. The velocity measurement error in case of the diagonal moving was 0.37mm/s-0.56mm/s, which was lager than the error 0.30mm/s in case of directly against moving.

In Fig.6, the measured size of the mesa was about 15.6mm × 14.4mm in width and height, respectively. Therefore, the size error 6.4mm × 7.6mm was within the estimated error of 15.6mm × 15.2mm (2MSLx × 2MSLy), and the thickness error was 0.4mm.

In Fig.7, the measured size of the mesa was about 14.8mm × 13.6mm in width and height, respectively. Therefore, the size error 7.2mm × 8.4mm was within the estimated error of 15.6mm × 15.2mm (2MSLx × 2MSLy), and the thickness error was 0.4mm.

In Fig.6 and Fig.7, the white circles represent the measured points, and the lattice points drawn by solid lines represent reconstructed points. Each of the lattice points is reconstructed by adding each proper shift caused by the velocity to the corresponding point finally transformed.

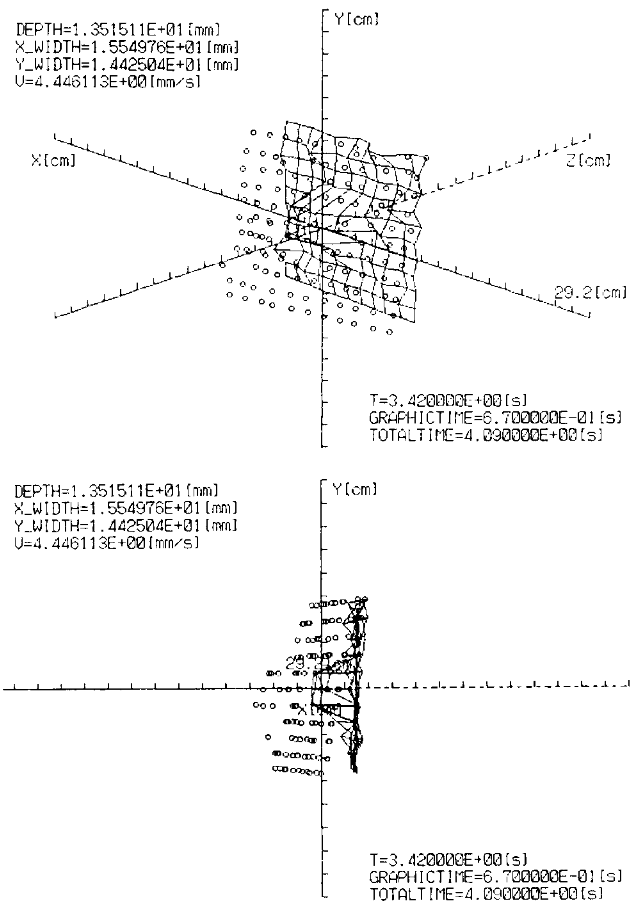


Fig.6 Reconstructed image of a square mesa on the plane departing from the mirror.

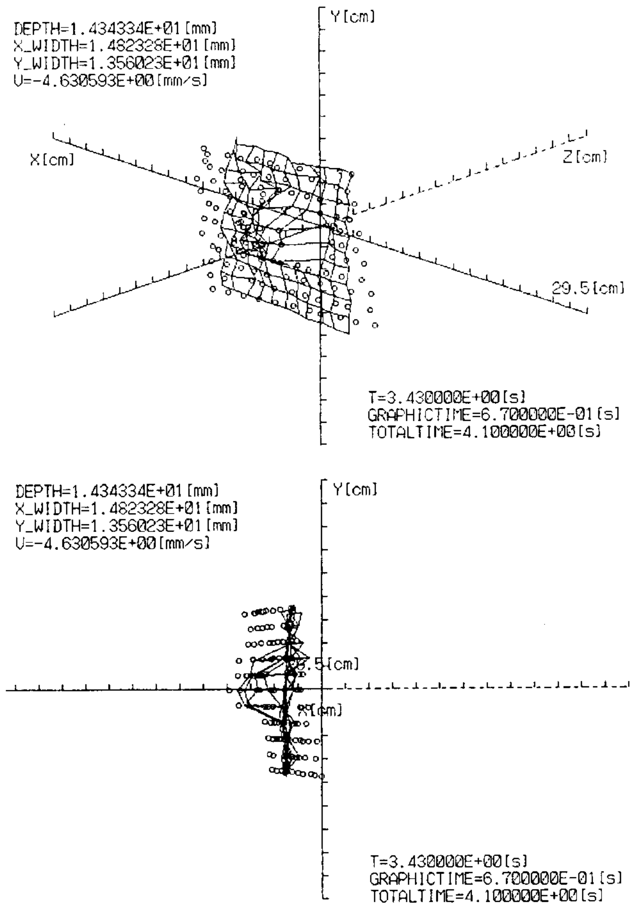


Fig.7 Reconstructed image of a square mesa on the plane approaching to the mirror.

4. CONCLUSION

We measured a 3-D range-image of an object diagonally moving against a laser light beam, using a range-finding speedometer, which is emitted from a self-mixing laser diode and mechanically scanned.

In the proposed measuring system, we employed a new data processing method, which enabled us to acquire the 3-D range-image which is observed not only from the optical axis but from a point in front of the moving object. We successfully acquired the 3-D range-image of a moving square mesa on a square plane, and the measured size parameters of it and its velocity.

The data processing method will be useful to acquire a 3-D range-image of each of parts or works which are carried on a belt conveyer at regular intervals in line.

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