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FAST 3-DIMENSIONAL PROFILE MEASUREMENT USING SLIT-RAY PROJECTION METHOD

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Abstract:
This paper describes a system which enables a fast 3-dimensional profile measurement using a slit-ray projection method. One distinctive feature of this system is that a real-time video processor is employed in order to reduce the amount of image data to be processed without eliminating essential information. Experimental results show that a calibrating method presented for the TV camera and the slit-ray projector is convenient and enables sufficient accurate measurements.

1. Introduction

The use of 3-dimensional information about solid objects is attractive in various fields, especially assembly and test process in the industrial automation domain. In order to obtain 3-dimensional information about solid objects, some methods have been developed up to now. One is based on the stereometric technique with two TV cameras and another one is to use the Moiré or interference fringe patttern. While the stereometlic technique has an advantage that the 3-dimensional data can be obtained rapidly, the computational complexity to find sets of corresponding points between the two video images and to solve nonlinear equations remains. The method to use Moiré or interference fringe pattern gives 3-dimensional undulation pattern of the objects, however, the information about the absolute 3-dimensional position of the solid object can not be obtained from the fringe pattern.

Among the method to give the 3-dimensional information a laser slit-ray projection method has a distinctive advantage that the information about 3-dimensional position of the solid object can be computed with simple equations and the information about multiple points on the solid object along the slit-ray can be obtained from a single frame data. Shirai presented a pioneer work about the slit-ray projection method, where his concern was mainly about the recognition of the object using the 3-dimensional information about the object. Researches on the slit-ray projection method up to now are concerned about the recognition of the object, the improvement of the system in order to eliminate the unmeasurable portions of the object inevitable to this method, stochastic data processing in order to increase the accuracy of the measurement and the improvement of the sampling speed. While slit-ray projection method gives the 3-D information about multiple points on the object, scanning across the solid objects is necessary. Sometime more than a few minutes are required to scan a scene and to give a low-level image processing. The improvement of the sampling speed is indispensable in order to implement the slit-ray projection method in the industrial factory.

This paper describes a system which enables a fast 3-dimensional profile measurement using a slit-ray projection method. The system developed in this study consists of a laser beam scanner to project a slit-ray on the solid object, a CCD TV camera to sample the scene of the slit-ray, a real-time video processor to extract essential informations about the 3-dimensional positions of the object and a 16-bit computer to control the total system and to perform data-processing like a computation of the 3-dimensinal coordinates of the sampled points and a wire-frame representation of the result obtained.

One distinctive feature of this system developed is that a real-time video processor is employed in order to reduce the amount of image data to be processed without eliminating essential information. Also Ozeki, et al. developed a real-time range measurement system using a slit-ray projection method, which adopted a low-resolution CCD TV camera in order to enable real-time calculations of the target points. Comparing their system with ours, a real-time processor employed in our system performs a more skillful processing like a thinning ,and more accurate measurement is possible.

Another feature of our system is that a calibration method of geometric parameters of the TV camera and slit-ray projector is employed. Only by sampling slit-ray images projected on a rectangular prism whose geometric height is already known, the calibration of the slit-ray projector can be achieved. Due to this calibration employed, operators can be free from cumbersome settings of the TV camera and the slit-ray projector.

The first part of this paper describes a system whereby the 3-dimensional information about an actual object or scene can be obtained, and explains a real-time processor utilized to extract the useful information. The second part shows how the calibration and the measurement are achieved. Furthermore, the experimental results are shown.

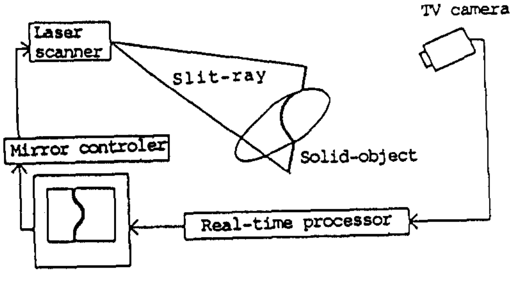


Fig.1 System configuration

2. 3-D Profile Measurement System

The setup of the 3-dimensional profile measurement system developed here is shown in Fig.1. A slit-ray is projected on a solid object, to be scanned, using two galvanometer mirrors. One rotates sinusoidally with 300 Hz frequency to generate a slit-ray from a laser beam and the other mirror is controled to rotates step wise so as to vary the orientation of the slit-ray and scan the slit-ray on the solid object. The TV camera samples the reflected light of the slit-ray projected on the solid object. The video signal of each picture is converted into a binary signal by a real-time video processor . Since binary slit-ray image, detected by TV. is usually broader than desirable, a horizontal thinning operation is given to obtain the raster coordinate of the center line. Each set of raster coordinates of the centerline extracted from every frame data are stored on a temporary memory. In order to obtain gloval profile of the solid objects, the laser slit-ray is scanned on the scene. After receiving all data about the scene from the temporary memory, a 16-bit computer (NEC PC-9801VM) caluculates the world coordinates of the slit-ray projected on solid objects.

3. Real-time video processor

Our system developed employed a real-time video processor, which extract the important information from the video signal and reduce the amount of image data to be processed. Owing to this real-time video processor, fast sampling and effective usage of memory become possible.

First, this real-time video processor digitize the video signal to one bit with 256x 256 pixels per a frame. Since binary slit-ray image sampled is usually broader than desirable, a horizontal thinning operation is given to obtain the raster coordinate of the centerline. Therefore, it is preferable to settle the TV camera so that the horizontal scanning line of the TV camera perpendicularly intersects the slit-ray image.

A block diagram of the real-time video processor is shown in Fig.2. A timing chart of this processor is also shown in Fig.3, where the signals are shown during the period of the m-th horizontal scanning. When the rise of binary video signal is detected (at P1 in Fig.2), Edge detector activates Edge signal ⊕ and the raster coordinate n1 is preset into Counter 1. Moreover, when the fall of binary video signal is detected (at P2 in Fig.2) Edge detecter activates Edge signal ⊖ and the data in Counter 2 and Counter 3 is stored in the memory. Since incrementing speed of Counter 2 is reduced to half by the frequency divider, output data of Counter 2 becomes (n1+n2)/2 which corresponds to the horizontal raster coordinate of the midpoint of P1 and P2. Output data of Counter 3 is the vertical raster coordinate m. Just after one vertical scanning on the TV camera has finished, all data stored in the memory are transfered to a 16-bit computer.

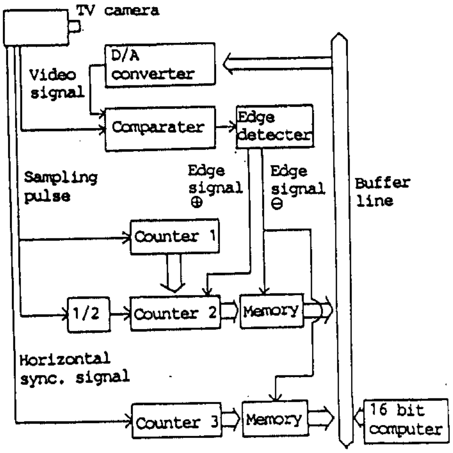


Fig.2 Block diagram of real time video processor

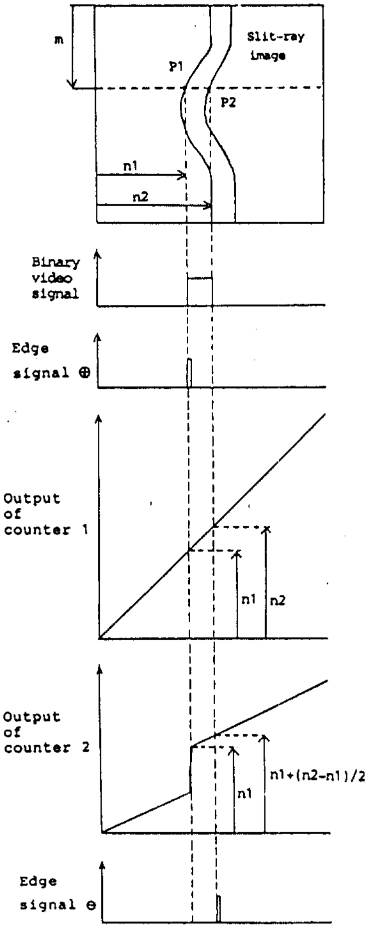


Fig.3 Timing chart

4. Calibration

Before determing the 3-dimensional position of object points by means of trigonometry, the calibrations of the TV camera and the laser slit-ray projector are necessary. In our system developed the world coordinate system is fixed on the table, the X-axis and the Y-axis on the table, the Z-axis, extending perpendicularly upward. The relationship between 3-dimensional points in the world coordinate system and the corresponding 2-dimensional points in the raster coordinate system is essentially a perspective transformation. Let the world coordinates of the object point be xi, yi, zi and cooresponding raster coordinates be ui ,vi. Then the following equation is satisfied,

$$\lambda \begin{pmatrix} ui \\ vi \\ 1 \end{pmatrix} = \begin{pmatrix} h11 & h12 & h13 & h14 \\ h21 & h22 & h23 & h24 \\ h31 & h32 & h33 & 1 \end{pmatrix} \begin{pmatrix} xi \\ yi \\ zi \end{pmatrix} \qquad (1)$$

where the element hij represents the relationship between the two coordinates.

Based on a minimum square error technique, six distinguished noncoplanar points whose world coordinates are already known are chosen to determine the value hij . For the six points chosen, Eq.(1) can be rewritten

$$Th = w \qquad (2)$$

where

$$T= \begin{pmatrix} x1 & y1 & z1 & 1 & 0 & 0 & 0 & 0 & -u1x1 & -u1y1 & -u1z1 \\ 0 & 0 & 0 & 0 & x1 & y1 & z1 & 1 & -v1x1 & -v1y1 & -v1z1 \\ x2 & y2 & z2 & 1 & 0 & 0 & 0 & 0 & -u2x2 & -u2y2 & -u2z2 \\ 0 & 0 & 0 & 0 & x2 & y2 & z2 & 1 & -v2x2 & -v2y2 & -v2z2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & x6 & y6 & z6 & 1 & -v6x6 & -v6y6 & -v6z6 \end{pmatrix}$$

$$h= \begin{pmatrix} h11 \\ h12 \\ \vdots \\ h32 \\ h33 \end{pmatrix} , \; w = \begin{pmatrix} u1 \\ v1 \\ u2 \\ v2 \\ \vdots \\ v6 \end{pmatrix} .$$

Since the coefficient matrix T and the vector w in Eq.(2) is determined by the world coordinates and the corresponding raster coordinates of the six distinguished points, it can be shown that the solution of Eq.(2) is

$$h=(T^tT)^{-1} T^t w \qquad (3)$$

where the matrix $(T^tT)^{-1}T^t$ becomes the pseud inverse of the matrix T.

The procedure to obtain the data of the six distinguished points follows the method described by Agin et al.. First, a laser spot beam is projected on the point whose world coordinates are manually measured in advance. Next the raster coordinates of the spot beam image , sampled by TV camera, is measured by the real-time video processor. Repeating the above procedure, data of the six distinguished points are obtained.

Fig.4 shows a method employed to calibrate the slit-ray projection. The procedure is as follows . First, a slit-ray is projected on a rectangular prism whose geometric height is already known, where the control signal to set the inclination angle of the slit-ray is θ_1 . Next, after sampling the slit-ray image, three points on the slit-ray (P1, P2, P3 in Fig.4) are chosen to obtain the raster coordinates ui,vi (i=1~3) by the real-time processor. Since the height of the rectangular prism and the table gives z coordinates of points P1, P2, P3, Eq.(1) gives the world coordinates of P1, P2, P3 on the slit-ray. Elimination of λ in Eq.(1) gives

$$\begin{aligned} &(h11-u_i h31)x_i+(h12-u_i h32)y_i+(h13-u_i h33)z_i+h14=u_i , \\ &(h21-v_i h31)x_i+(h22-v_i h32)y_i+(h23-v_i h33)z_i+h24=v_i \end{aligned} \qquad (4)$$

where xi, yi, zi are the world coordinates of Pi(i=1, 2, 3) and ui, vi are the corresponding raster coordinates. Hence, the world coordinates of Pi(i=1, 2, 3) are obtained by

$$xi = \frac{1}{D} \begin{vmatrix} u_i-h14-(h13-u_i h32)zi & h12-u_i h32 \\ v_i-h24-(h23-v_i h33)zi & h22-v_i h33 \end{vmatrix} ,$$

$$yi = \frac{1}{D} \begin{vmatrix} h11-u_i h31 & u_i-h14-(h13-u_i h32)zi \\ h21-v_i h31 & v_i-h24-(h23-v_i h33)zi \end{vmatrix} ,$$

$$D=(h11-u_i h31)(h22-v_i h32)-(h12-u_i h32)(h21-v_i h31)$$

The world coordinates of points P1, P2, P3 determine the inclination of the slit-ray. Suppose the equation to express the inclination of the slit-ray is

$$Z= A(\theta_1)x + B(\theta_1)y + C(\theta_1), \qquad (5)$$

then coefficient $A(\theta_1)$, $B(\theta_1)$, $C(\theta_1)$ are determined by

$$\begin{pmatrix} x1 & y1 & 1 \\ x2 & y2 & 1 \\ x3 & y3 & 1 \end{pmatrix} \begin{pmatrix} A(\theta_1) \\ B(\theta_1) \\ C(\theta_1) \end{pmatrix} = \begin{pmatrix} z1 \\ z2 \\ z3 \end{pmatrix}$$

After changing the control signal to set the inclination angle of the slit-ray from $\theta 1$ to $\theta 2$, similar procedure mentioned above gives

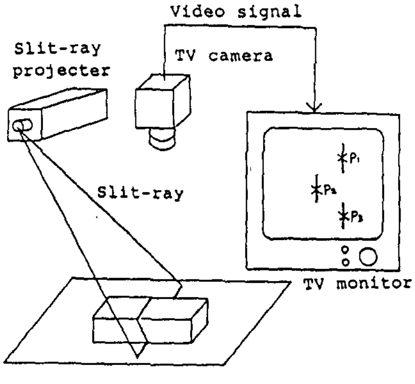


Fig.4 Calibration of slit-ray

$$Z = A(\theta_2)x + B(\theta_2)y + C(\theta_2) \ . \qquad (6)$$

Once Eq.(5) and Eq(6) are obtained the equations to express the inclination of the slit-ray, whose control signal is θ ,is determined by the interpolation formula as follows

$$Z = A(\theta)x + B(\theta)y + C(\theta) \qquad (7)$$

where

$$A(\theta) = \tan\left\{\left(\frac{\theta-\theta_1}{\theta_2-\theta_1}\right)\tan^{-1}(A(\theta_2)) + \left(\frac{\theta_2-\theta}{\theta_2-\theta_1}\right)\tan^{-1}(A(\theta_1))\right\},$$

$$B(\theta) = \tan\left\{\left(\frac{\theta-\theta_1}{\theta_2-\theta_1}\right)\tan^{-1}(B(\theta_2)) + \left(\frac{\theta_2-\theta}{\theta_2-\theta_1}\right)\tan^{-1}(B(\theta_1))\right\},$$

$$C(\theta) = \frac{(A(\theta)-A(\theta_1))C(\theta_2)+(A(\theta_2)-A(\theta))C(\theta_1)}{A(\theta_2) - A(\theta_1)}$$

After calibrations of the TV camera and the slit-ray projector, the 3-dimensional world coordinates x, y, and z of the target point can be determined from the raster coordinates u and v. It is obvious that linear equations (4) and (5), gives the 3-dimensional world coordinates by the Cramer's formula. The solution is self-evident and is omitted here.

5. Measuring procedure

Fig.7 shows the flow chart of a measuring procedure for our system.

At the begining the calibration program establishes a relationship between the 3-dimensional world coordinates fixed on the measuring table and the 2-dimensional raster coordinates fixed on the TV camera.

At the second step, the computer project the laser slit-ray on the object and obtains the raster coordinates of the resultant slit-ray image from the real-time video processor.

At the third step, the computer moves the laser slit-ray and obtain the raster coordinates again.

After repeating the above steps predetermined times (64 times in Fig.5), the computer starts to transform the 2-dimensional raster coordinates to the 3-dimensional world coordinates.

Finally, a feature extraction program or a recognition program starts.

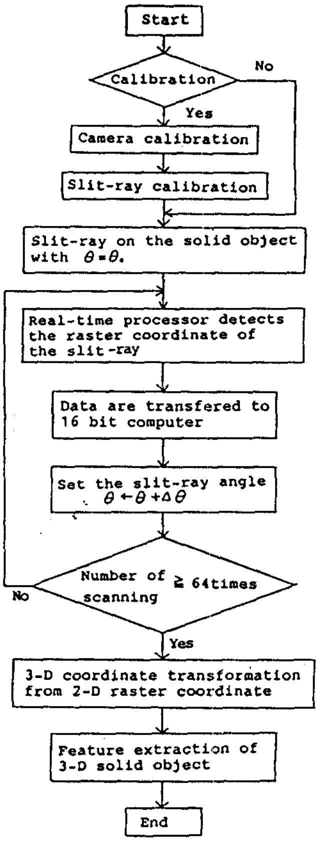


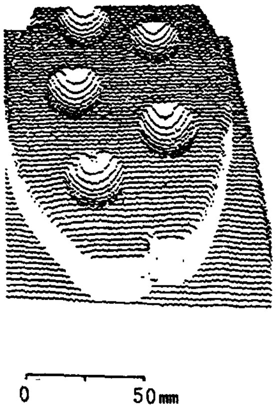
Fig.5 Flow chart of measurement

6. Experimental Results

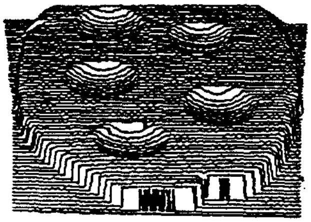
In order to test the utility of our system developed, two kinds of experimental measurements are performed.

Fig.5 (a) and (b) show one experimental result, the solid object are circular hollows (28 mm in diameter ,8 mm in depth) on the white clay board. In this case, the TV camera is settled 40 cm apart from the target object. Fig.5(a) shows a slit-ray image which is observed on the TV monitor. FIg.5(b) shows a result which is obtained after the transformation of the raster coordinates of the sampled points to the 3-dimensional world coordinates. By scanning the slit-ray on the scene, sixty four slit-ray image data are sampled. Since the type of the TV camera employed here is non-interlace, sixty frames image samling per a second is possible. Therefore, all the raster coordinates of the sampled points in Fig.5 are obtained in 1.1 second. Each raster coordinates ui and vi of the sampled points are stored as a 8-bit data in our sistem. This means that a 32 K-byte memory is sufficient to store all the 3-dimensional information of the clay board.

Fig.6(a) and (b) shows slit-ray images obtained by the real-time video processor. The experimental result of Fig.6(a) shows 128 slit-ray images obtained in 2.1 second. The result of Fig.6(b) shows 32 slit-ray images obtained in 0.5 seconds. Analysis indicates that the average absolute error in position measured by our system here is not greater than 2.0 milimeters.

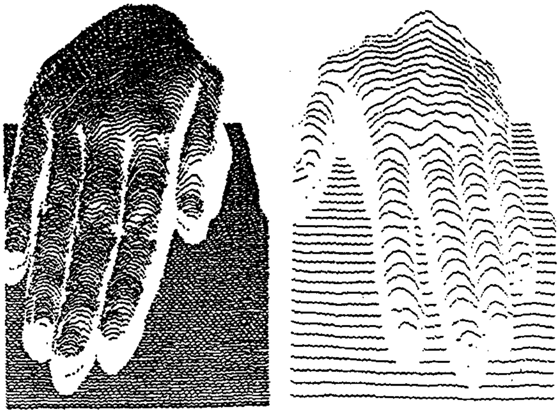


(a):64 slit-ray images



(b):Display of 3-D data

Fig.5 Measurement of circular hollows



(a):128 slit-ray images (b): 32 slit-ray images

Fig.6 Slit-ray images of hand

7. Conclusions

A system which enables a fast 3-dimensional profile mesurement using a slit-ray projection method is developed. Due to an employment of a real-time video processor, the extraction of the necessary information from the video signal is performed quickly, and the reduction of the amount of image data to be processed become possible. Experimental results shows that the method of calibrating the TV camera and the slit-ray projector used in our system is convenient and sufficiently accurate.

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