Fast Three-Dimensional Measurement Technique Using a Reference Table*
(Measurement of a Human Head)

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This paper describes a system which enables fast 3-dimensional measurement of a human head by means of a slit ray projection method. The system developed here consists of a laser slit ray projector, two CCD TV cameras, a real-time video signal processor and a 32-bit computer. Due to the employment of this real-time video signal processor and a fast data-processing technique using a reference table, a 3-dimensional measurement of the human head can be accomplished in 4.3 seconds, and all the image data are converted to 3-dimensional data in one second. Experimental data reveal the applicability of our system.

Key Words: Measurement, Human Engineering, Sensor, Laser, Image Processing, Slit-Ray Projection

1. Introduction

Non-contact and accurate 3-dimensional profile measurement is highly desirable in the fields of mechanical engineering, human engineering and also orthopedic surgery. Important points of the 3-dimensional profile measurement are how to obtain all 3-dimensional data as fast as possible, and how to convert all these data to 3-dimensional coordinates. The well-known Moire topography gives 3-dimensional data (Moire fringe image data) immediately, whereas, conversion of these data into 3-dimensional coordinates requires sophisticated image data processing and therefore takes more than a few minutes. On the other hand, the slit ray projection method takes more than a few seconds to obtain global profile data of the target object; however, conversion of these data into the 3-dimensional coordinates is so simple that only a few seconds are required.

In order to enable more rapid 3-dimensional measurement a modified slit ray projection method has been developed where coded grid patterns are projected instead of a slit ray. Due to the employment of these coded grid patterns, the number of images to be processed was decreased. However, the conventional slit ray projection method still has the distinguished features that the measuring procedures are so simple that reliable data are obtained and calibration of the measuring system is readily achieved. Because of these features, the slit ray projection method is often preferable.

In this paper, we show one technique enabling fast 3-dimensional measurement of a human head. As mentioned before, the 3-dimensional profile of the human head is a concern in orthopedic and dental surgery. The principle of our measuring system is based on the slit ray projection method. One feature of our system is employment of the slit ray image proces-

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sor and fast data-processing algorithm to convert the image data to 3-dimensional coordinates. As a result, 3-dimensional data of forty thousand points on the human head can be obtained in 4.3 seconds and this data can be converted into 3-dimensional coordinates in 1.0 second.

The function of our slit ray image processor is to obtain the raster coordinates of the slit ray image using the original hardware logic circuit. The fast data-processing algorithm developed here uses a reference table where data of representative points are converted and tabled as a reference table in advance. Due to this reference table, fast data conversion becomes possible without the use of a high-speed arithmetic processor such as digital signal processors.

2. Measuring System

The setup of our 3-dimensional profile measuring system of the human head is shown in Fig. 1. A laser slit ray is projected onto the human head from the tip of the rotating arm. The slit ray is generated from the laser beam (output power 2 mW and wavelength 760 nm) with a rotating polygon mirror. Two CCD TV cameras to detect the slit ray images are also mounted on the rotating arm which rotates around the human head to obtain a global profile. While only one TV camera is enough to obtain 3-dimensional data, another camera is introduced so that the unmeasurable portion can be diminished. Optical band-pass filters are attached to the camera to eliminate the effects of external lights. The video signals of these cameras are simulataneously sampled and converted

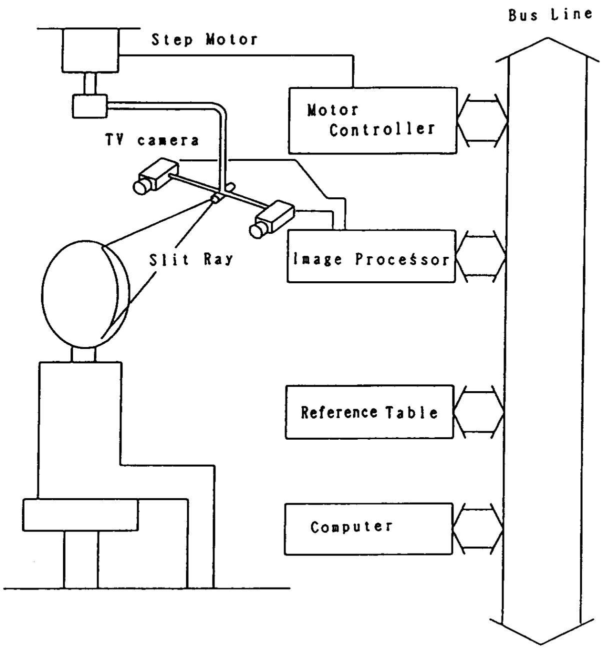

Fig. 1 Setup of measuring system

into 8-bit digital signals. Immediately after the slit ray image processing unit detects the raster coordinates of the centerline of the laser slit ray, a 32-bit computer (NEC PC 9801RA) reads out the data and stores them in the memory. Once all the data around the human head are obtained, the data are converted into 3-dimensional coordinates using the reference table which includes information about the geometrical setting of the measuring system and the image distortion caused by lens aberration.

The results are displayed graphically.

3. Data Compression by the Slit Ray Image Processor

Our system employed a slit ray image processor, which extracts essential information from the slit ray image and reduces the amount of image data to be processed. Using this slit ray image processor, fast sampling and effective usage of memory become possible. Two CCD cameras are synchronized with external synchronous signals.

First this slit ray image processor digitize the video signals to 8-bit signals with 512×240 pixels per frame. Since the slit ray image is usually broader than desirable, a horizontal searching operation is given considering the lighting level. It is important to note that cameras are mounted on the arm so that the horizontal scanning line of the TV cameras intersects the slit ray perpendicularly.

A block diagram of the slit ray image processor is shown in Fig. 2. Considering that the video signals show the maximum level where the slit ray is projected, this processor is designed to give the horizontal raster coordinates where the video signals show the maximum level. Generally, the resolution of CCD TV cameras is limited by the number of pixels on the CCD semiconductor chip. However, considering the light level of every pixel, higher resolution can be attained. Therefore, the light level of every pixel is considered here.

Second, the 8-bit video signal of 3 consecutive pixels $(P(u-1, v), P(u, v)$ and $P(u+1, v))$ are compared. If the second pixel $P(u, v)$ has the maximum level in these three pixels, the raster coordinates $u+\varepsilon$ where the actual laser slit ray might be settled is estimated. ε can be readily estimated considering the two-dimensional interpolation formula. ε is limited in the region $(-1<\varepsilon<1)$. Sine ε can be determined by the differences of the 8-bit video signals $(P(u, v)-P(u-1, v)$ and $P(u, v)-P(u+1, v))$, determination of ε can be simplified to a looking-up task of the ROM table, as shown in Fig. 2. The horizontal raster coordinate is stored in COUNTER1 and the vertical raster coordinate is stored in COUNTER2. Therefore, immediately after every horizontal scanning is completed, the computer reads out the output of ROM table ε, the output of COUNTER1 u and the output of COUNTER2 v. The computer then again stores the data.

4. Technique for Use of Reference Table

Since our system gives the data of more than forty thousand points, a fast technique to process the large number of data in a few seconds is needed. Therefore, we introduced a reference table, containing all the information about the aberration caused by the TV camera lens and about the relationship between the raster coordinates of the target points and the 3-dimensional coordinates.

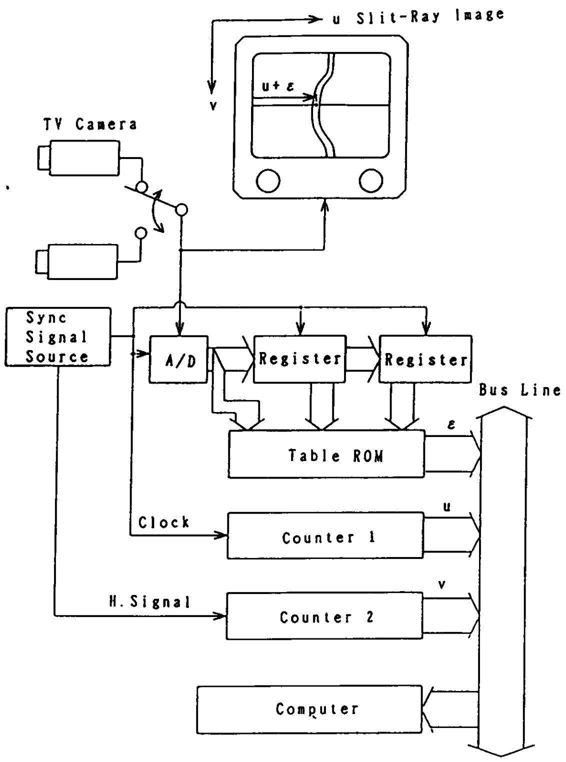

Fig. 2 Block diagram of image processor

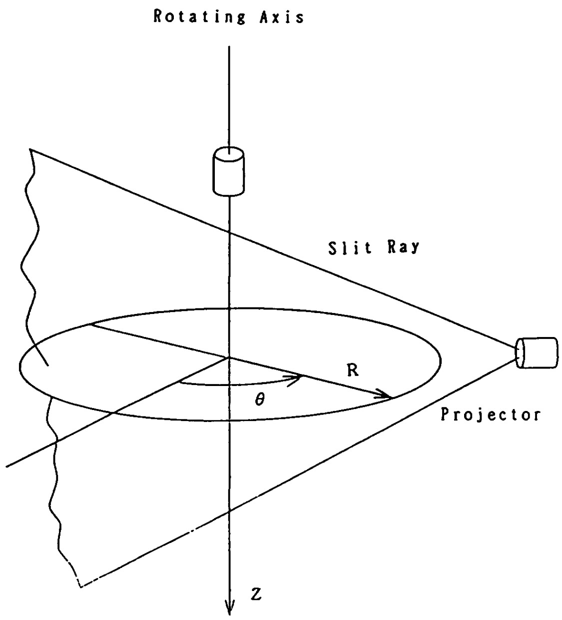

Fig. 3 Geometrical relationship

In order to realize practical 3-dimensional measurements, we employed a geometrical relationship, as is shown in Fig. 3, where the z-axis is coincident with the rotating axis of the rotating arm and also the z-axis is on the slit ray plane. This means that the slit ray projector needs to be adjusted so that the projector projects slit rays on the rotating axis.

4.1 Calibration of the camera system

The perspective transformation formula gives the relationship between the 3-dimensional coordinates (x, y, z) and the corresponding raster coordinates (u, v) as the following equation:

$$\lambda\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}h_{11}&h_{12}&h_{13}&h_{14}\\h_{21}&h_{22}&h_{23}&h_{24}\\h_{31}&h_{32}&h_{33}&1\end{bmatrix}\begin{bmatrix}x\\y\\z\\1\end{bmatrix}, \qquad (1)$$

where h_{ij} are parameters to represent the geometrical configuration of the camera system. Generally, the calibration of the camera system corresponds to determining these parameters. Already one calibration method has been developed. Following this method, raster coordinates (u, v) of six distinguished points whose 3-dimensional coordinates are known in advance are measured by the camera system. Then, parameters h_{ij} are determined so that Eq. (1) can be satisfied in the least squared error.

Since we consider the geometrical relationship in Fig. 3, a simpler calibration can be executed. Considering that the target points lie on the slit-ray plane, the relationship between the cylindrical coordinates (R, θ, Z) and its corresponding raster coordinates (u, v) can be represented by

$$\lambda\begin{bmatrix}u\\v\\1\end{bmatrix}=\begin{bmatrix}h_{11}&h_{12}&h_{13}\\h_{21}&h_{22}&h_{23}\\h_{31}&h_{32}&1\end{bmatrix}\begin{bmatrix}R\\Z\\1\end{bmatrix}, \qquad (2)$$

Elimination of λ in Eq. (2) gives

$$\begin{aligned}(h_{31}R+h_{32}Z+1)u&=h_{11}R+h_{12}Z+h_{13},\\(h_{31}R+h_{32}Z+1)v&=h_{21}R+h_{22}Z+h_{23}.\end{aligned} \qquad (3)$$

The above relationship is valid for any of the points on the slit-ray plane. Therefore, for n sets of coordinates (R_i, θ_i, Z_i) and (u_i, v_i) $(i=1, 2, \cdots, n)$ the following relationship is established:

$$\boldsymbol{T}\cdot\boldsymbol{h}=\boldsymbol{w}, \qquad (4)$$

where

$$T=\begin{bmatrix} R_1 & Z_1 & 1 & 0 & 0 & 0 & -R_1u_1-Z_1u_1 \\ 0 & 0 & 0 & R_1 & Z_1 & 1 & -R_1v_1-Z_1v_1 \\ R_2 & Z_2 & 1 & 0 & 0 & 0 & -R_2u_2-Z_2u_2 \\ 0 & 0 & 0 & R_2 & Z_2 & 1 & -R_2v_2-Z_2v_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \quad \vdots \\ 0 & 0 & 0 & R_n & Z_n & 1 & -R_nv_n-Z_nv_n \end{bmatrix},$$

$$h=\begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ \vdots \\ h_{32} \end{bmatrix}, \quad w=\begin{bmatrix} u_1 \\ v_1 \\ u_2 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}.$$

In the above equation, matrix $\boldsymbol{T}$ and vector $\boldsymbol{w}$ can be determined by measuring n points on the slit ray plane. By measuring more than four points vector $\boldsymbol{h}$ can be determined in the least squared error as

$$\boldsymbol{h}=(\boldsymbol{T}^t\cdot\boldsymbol{T})^{-1}\boldsymbol{T}^t\boldsymbol{w}, \qquad (5)$$

where $(\boldsymbol{T}^t\cdot\boldsymbol{T})^{-1}\boldsymbol{T}^t$ is the pseudo inverse of matrix $\boldsymbol{T}$.

Once the vector $\boldsymbol{h}$ is determined, Eq. (3) can be rearranged as

$$\begin{bmatrix} R \\ Z \end{bmatrix}=\begin{bmatrix} h_{31}u-h_{11} & h_{32}u-h_{12} \\ h_{31}v-h_{21} & h_{32}v-h_{22} \end{bmatrix}^{-1}\begin{bmatrix} h_{13} \\ h_{23} \end{bmatrix}. \qquad (6)$$

This equation gives the transformation formula from raster coordinates (u, v) to cylindrical coordinates (R, θ, Z).

4.2 Correction of lens aberration

In order to realize accurate measurement, correction of lens aberration is required. By measuring the tip of the pen of an x-y plotter we made a table to convert the raster coordinates (u, v) to the corrected raster coordinates (u_c, v_c). Considering the memory consumption, only 64 points each in the x- and y-directions are measured and the data tabled. Since the coordinates of only 64×64 points are tabulated, a linear interpolation formula is also used to correct any raster coordinates (u, v).

4.3 Generation of conversion table

For all possible points (u_c, v_c) in the correction table of the lens aberration, cylindrical coordinates R and Z are calculated by Eq. (6) and the results are also tabulated. After that the resultant table and the table of the lens aberration are incorporated into one reference table, as shown in Fig. 4. Using this reference table, data u and v obtained with the slit ray image processor can be readily converted to cylindrical data R and Z with accuracy. The table is only limited for some representative points, and linear interpolation is also used for nonrepresentative points.

The procedure to measure a human head is summarized as follows. Firstly, the computer in Fig. 1 receives more than forty thousand data (u, v) from the slit ray image processor during one rotation of the rotating arm.

Secondly, the computer converts all these data (u, v) to cylindrical data (R, Z) using the reference table or interpolation formula on the reference table. Since the coordinate θ corresponds to the rotation angle of the rotating arm, θ can be easily determined by referring to the memory address of the u, v.

The cylindrical data are stored in the computer, and representations such as a wire-frame, surface model or cross-sectional can be selected. Here again, another reference table to convert cylindrical data (R, θ, Z) into raster coordinates on the computer CRT is employed so that rapid representations become possible.

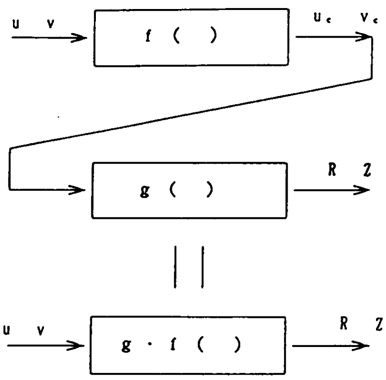

Fig. 4 Configuration of reference table

5. Experimental

In order to test the applicability experiments were performed using our system with an arm length of 50 cm and a deviation angle between the TV cameras and slit ray projector of 30 degrees.

Firstly, cylinders with different diameters were measured. As shown in Table 1, the cylinder diameters could be measured with an error of less than ±0.5 mm.

Fig. 5 shows one experimental data where 256 slit ray images were processed. It took 4.3 seconds to obtain the output data from the slit ray image processor, one second to convert forty thousand raster coordinates into cylindrical coordinates and another one second to represent the result graphically.

Another experimental result is shown in Fig. 6

Table 1 Accuracy of measuring system

[mm]

No	Diameter	Measured Data
1	130.1	130.4
2	135.2	135.0
3	140.2	140.6
4	145.4	145.6
5	150.3	150.8

Fig. 5 Experimental result of human head

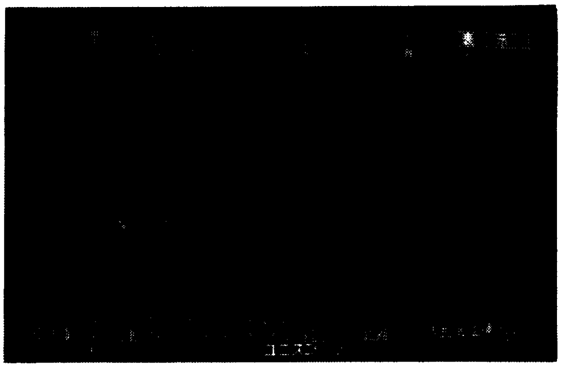

Fig. 6 Experimental result of mannequin

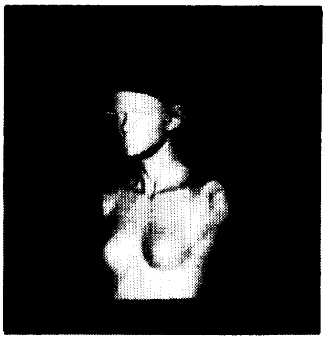

Fig. 7 Surface model of mannequin

where the upper body of a mannequin was measured. In this case the length of the rotating arm was changed to 90 cm. While the accuracy deteriorated to ±2.0 mm, a 3-dimensional profile of the mannequin's chest was clearly measured. In Fig. 7 a surface model representation is shown, where it took only one second even on a conventional personal computer.

All the above measurements were performed under normal lighting conditions.

6. Conclusions

A system to measure the 3-dimensional profile of a human head was developed. Rapid data processing is possible due to the employment of a slit ray image processor and an algorithm for the use of a reference table.

Two cameras are mounted so that the unmeasurable portions inevitable to this method can be eliminated as much as possible. There still remain some portions where 3-dimensional data could not be obtained ; examples shown in Fig. 7 are the surfaces behind the ear or beneath the chin. In order to improve the performance of this system, intensive consideration of the geometrical arrangements including the number of TV cameras is required.

In this system, 3-dimensional data of the human head were compressed and stored in 128 k byte memory. We now intend to connect the data to a 3-dimensional data edit system such as a marketed CAD/CAM system to be able to utilize the data more effectively.

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