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3-D Measuring System of Huge Structures Using Laser Spot-Ray Projection

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Abstract

We present a system to measure 3-dimensional coordinates of huge structures like ships, buildings and oil tanks. Two important units are a laser spot projector and a laser spot tracker. Employing a tactful image processing , our system has some features :e.g. compactness, cost , accuracy and robustness to hazardous emvironments.

1. Introduction

Nowadays 3-dimensional measuring techniques like stereometric method, Moire interference fringe pattern method and laser range finder method are presented.[1~4] While these techniques give us basic approaches to 3-D measurements, many problems occures if the size of the target body overs a few meters;e.g. buildings, ships and oil tanks .

One powerful technique to answer these problems is a well-known method to measure points on the target body using two latest surveying instruments called transits or theodolites, based on the principle of trignometric survey. In order to realize this technique as a practical automatic 3-D measuring system, all manual tasks needs to be replaced with computer control. We proposed one example as an automaic 3-D measuring system using two digital theodolites in the last KACC.[5]

In this paper we present another new system to measure the 3-dimensional shape of structures whose sizes over several meters. Without using surveying instruments, we realized an automatic measuring system which has high accuracy . Two important units of our system are one laser spot projector and one laser spot tracker, those are more compact ,more suitable for computer control and less expensive than latest surveying instruments. The laser spot projector is controlled to project laser beam in the pre-programmed directions. Whereas, the laser spot tracker is controlled to detect the direction of the laser spot. Accounting the direction of the laser spot projector and the laser spot tracker, 3-dimensional coordinates of the laser spot on the target body can be determined. In order to reduce mechanical movements and realize accurate and fast measurements, directions of the laser spot projector and the laser spot tracker are controlled with two mirrors. These two mirrors are rotated with fine-step step-motors. A tactfull image analysis is performed on the laser spot tracker so that accurate and fast measurement is realized and also that the system is robust for the lighting condition.

In the practical field, a target body might have irregular shapes. Therfore, measurements from only one direction sometimes offers insufficient data.In order to enable measurements from other directions without moving measuring systems a mirror can be used efficiently. Since our system can easily measure the orientation and the position of the mirror, 3-dimensional data on the side or in the rear of the target body can be obtained easily.

A series of experimental results to test the the accuracy and applicability of our system indicate that out system has excellent characteristics.

2. 3-D Measuring System

The setup of our 3-dimenaional measuring syetem is shown in Fig.1. This system is composed of one laser spot projector, one laser spot tracker and a system controller.

On the laser spot projector a laser emitting tube at a wave length of 632.8 nm with 3 mW is mounted. The laser beam is reflected with two mirrors to project the laser spot with 2 mm in diameters in the pre-specified direction. Two mirrors are

rotated with fine-step motors which have harmonic drive reduction mechanisms to reduce mechanical errors. Due to these fine-step motors, resolution of rotating angle of mirrors is 0.0018 degree.

A laser spot tracker is used to detect the direction of the laser spot on the target body. As is shown in Fig.1, at the end of a sighting tele-scope, one CCD TV camera is mounted to detect the laser spot. The orientation of the sighting tele-scope is controlled using the same mechanism with the laser spot projector.

An image processing unit performs 8-bit gray scale image data processing with 512×480 pixels per frame obtained by the CCD TV camera , and gives raster coordinates of the gravity center of the laser spot. In order to reduce the error caused under the the hazardous lighting environments,following an image-subtraction technique is used. Suppose that the laser spot projector and laser spot tracker are settled. First, emission of laser is stopped and a background image is stored into the frame memory . Next,the laser beam is emitted and the laser spot image is also stored into the frame memory. Subtracting the first image from the second image, the image processing unit obtains more stable detection of the center of the laser spot without any effects of background image.

Computer calculates the coordinates of the laser spot on the target body from the data;e.g the orientation of the laser spot projector, the orientation of the laser spot tracker and the raster coordinates of the gravity center of the laser spot . It shoud be noted that it is not needed to control the orientation of the laser spot tracker to detect the laser spot at the center of the raster coordinates. It is needed to control the orientation of the laser spot tracker to detect the laser spot around the center of the raster coordinates. The reason is that deviation of the orientation of the laser spot tracker can be easily calculated using raster coordinates of the gravity center of the laser spot.

3. Determination of 3-D coordinates

On determining the 3-D coordinates of target points, the geometrical setup of the laser spot projector and the laser spot tracker should be calibrated in advance.

Calibration

Based on a minimum squared-error technique, measurements of more than six distinguished noncoplanar base points realize the calibrating process. We summarize those results briefly.

Let world coordinates of a target point be x,y,z and the corresponding azimuth and elevation angles be θ and ϕ which are obtained by our laser spot projector and laser spot tracker . Due to the principle of perspective transformation, the following equation establishes,

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

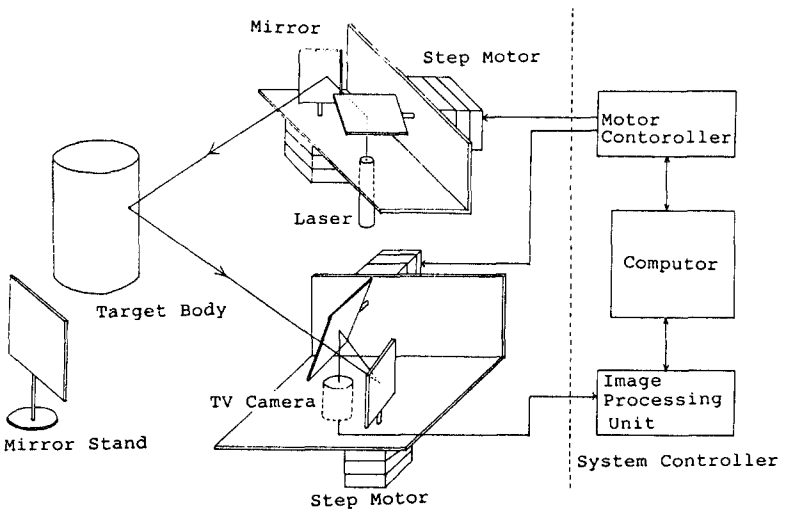

Fig. 1 System Setup

where u and v represent $\tan\theta$ and $\tan\phi$ respectively , and elements hij represents the geometrical relationship. Substituting all data ui,vi obtained by measurements of the i-th base points whose coordinates xi,yi,zi (i=1 ~ 8) are known in advance into Eq.(1), we need to determine elements hij so that Eq.(1) can be satisfied in the minimum squared-error meanings.

The geometrical configuration of the laser spot projector and that of the laser spot tracker can be calibrated in the same manner using Eq.(1).

Tracking of laser spot

Once geometrical arrangements of our system are calibrated, measurements of 3-D positions become possible. One important problem to realize an accurate and fast measurement is to adjust the orientation of the laser spot tracker to detect the laser spot around the center of the tele-scope. In worse cases the laser spot tracker often fails to detect the laser spot in the sight. In such a case, the laser spot tracker needs to search the laser spot with rotating two mirrors.

Here, we introduce one technique to search the laser spot efficiently.

Using vector matrix notations, Eq.(1) for the laser spot projector can be rearranged as folows

$$Dx = b \tag{2}$$

$$D = \begin{bmatrix} h_{31}u-h_{11} & h_{32}u-h_{12} & h_{33}u-h_{13} \\ h_{31}v-h_{21} & h_{32}v-h_{22} & h_{33}v-h_{23} \end{bmatrix}, \quad b = \begin{bmatrix} h_{14}-u \\ h_{24}-v \end{bmatrix}$$

Vector x to satisfy Eq.(2) can be represented by

$$x = g + f\varepsilon \tag{3}$$

$$g = D^T(DD^T)b, \quad f = d_1 \times d_2$$

where $D^T(DD^T)$ is a pseudo inverse of matrix D , vector di is i-th column vector of D and ε is an indefinite scalar number. Since the laser spot lies on a line represented with Eq.(3), the orientation of the laser spot tracker to search the laser spot can be limited as follows.

Substitution of Eq.(3) into Eq.(1) to represent the posture of the laser spot tracker gives

$$\varepsilon = -\frac{(h_1-h_3u)^T g+h_{14}}{(h_1-h_3u)^T f} \tag{4}$$

$$v = \frac{h^T{}_2\,(g+f\varepsilon)+h_{24}}{h^T{}_3\,(g+f\varepsilon)+1} \tag{5}$$

$$h_1 = \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \end{bmatrix} \quad h_2 = \begin{bmatrix} h_{21} \\ h_{22} \\ h_{23} \end{bmatrix} \quad h_3 = \begin{bmatrix} h_{31} \\ h_{32} \\ h_{33} \end{bmatrix}$$

where hij are parameters defined by Eq.(1) for the laser spot tracker.

Eq.(4) means that once azimuth angle of laser spot tracker is settled, parameter ε is determined. And once ε is determined, elevation angle ϕ of the laser spot tracker to detect the laser spot is determined by Eq.(5) and x,y,z coordinates are determined by Eq.(3).

This means that once azimuth angle θ or u (= $\tan\theta$) of the laser spot trackeris settled, elevation angle ϕ or v (= $\tan\phi$)is automatically determined. This fact brings some features. Fig.2 shows one image of laser spot to be processed. Our image processing unit searches the laser spot only on the line represented in Eq.(3) , image processing is performed only on the dotted line as shown in Fig.2 . Therefore, the amount of image processings is extremely reduced.

Furthermore, we are often able to reject unfavorable secondary reflected images, which may occure when the undulation of the target surface is so strong as show in Fi.2.

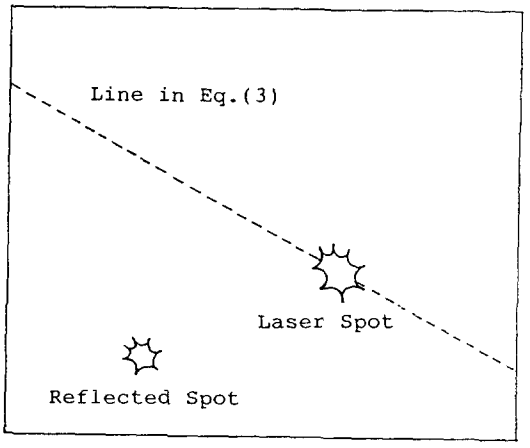

Fig. 2 Image of Laser Spot

Measurement using rear-view mirrors

3-D data on the side or in the rear of the target body can not be obtained by the measurement from the one direction. However, using a side-view and rear-view mirorr enables such a measurement without moving the measuring system. When we intend to use the rear-view or side-view mirrors, mirrors need to be calibrated with accuracy. Using the feature of our system , the posture of mirrors can be calibrated readily by measuring one point and its mirror images in the mirror.

A principle to calibrate the mirror is shown n Fig.3, where Pr is the point to be measured and Pm is the mirror image of Pr. We denote those position vector pr and pm respectively. The normal vector of the mirror is obtained as follows

$$n = \frac{|p_1|^2-|p_2|^2}{2|p_1-p_2|^2}(p_1-p_2) \qquad (6)$$

Once the normal vector of the mirror is obtained, 3-D coordintes of Pm in the mirror can be transfered to those of Pr by the following equation

$$P_r = P_m - \frac{2n^T P_m}{|n|^2} n + 2n \qquad (7)$$

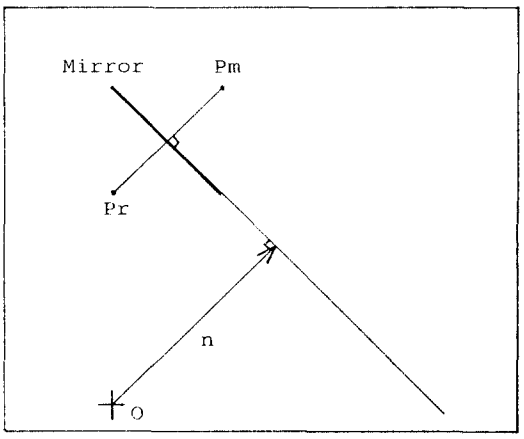

Fig. 3 Calibration of Mirror

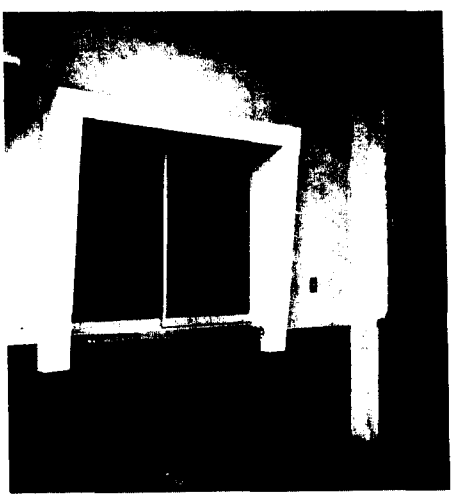

Photo. 1 Target Wall

4. Experiments

In order to test the utility of our measuring system, we measured 3-D coordiantes of a wall of our laboratory which is shown in Photo.1. Fig.4 shows data of our experimant, where 7000 points of data are obtained. The laser spot projector and laser spot tracker are settled 8 meters apart from the wall. This measurement took about 1 hours. Experimental results show that maximum absolute error in position were less tha 3 milimeters. This experiment was executed outside on the cloudy day.

5. Conclusion

A system to measure 3-dimensional shapes of huge structures are presented. The 3-dimensional shape is measured by projecting a laser spot with a laser spot projector and tracking the laser spot with the laser spot tracker. Triangulation is used to determine the location of target points.

Comparing with the system we proposed at last KACC, our new system has much superiority; e.g. compactness, cost, speed, and robustness.

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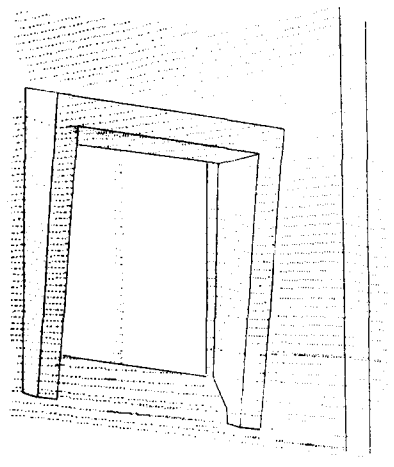

Fig. 4 Experimental Data

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