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3-D Measuring System of Structures and Pressure Vessels

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Abstract.

A system for 3-dimensional measurement of structures like buildings , pressure vessels and ships is presented. Two electric transits , which are latest surveying instruments, are controlled with a computer in order to scan the target surface of the object. An image processing unit relieves the operator of the burden of manual adjusting for forcusing the sighting tele-scope.

1.Introduction

Nowadays 3-dimensional measurements of huge pressure vessels, structures and ships are carried out mainly by conventional manual tasks. Therefore , informations about the 3-dimensional shapes of these objects often become not sufficient and not accurate

Furthermore , if more than hundreds of sample points are required some hours might be spent to finish the measurement.

Of course , much efforts have been devoted to measuring and determining 3-dimensional geometry of objects by many researchers . And successful methods have been presented, they are a stereometric method,[1] Moire or interferenc fruge pattern method[2] and a laser range finder method .[3][4] While these methods give us basic principles of 3-dimensional measurements , many problems appear if the size of target body overs a few meters.

In this paper , we present a system to measure 3-dimensional shapes of structures and pressure vessels whose sizes over several meters . Basing the principle of trignometric survey ,two electrical transits, which are wellknown as latest surveying instruments , are employed in order to enable an accurate 3-dimensional measurement. Although 3-dimensional measurements to use two electrical transits are adopted in some special field like shipyards and construction sits, operations of these transits depend on the manual adjustment.

However , the system presented here is highly automated. In stead of manual adjustments and read-out , an image processor introduced in our system recognizes the images obtained through the sighting tele-scope and controls the directions of two electrical transits .

One electrical transit is reconstructed to be a laser spot projector , whose azimuth corner and elevation can be controlled to project a laser beam on the target surface following programmed sequences with absolute angle error less than 1 second . The other transit is reconstructed to be a laser tracker , whose azimuth corner and elevation are controlled to detect the laser spot at the center of the sighting tele-scope. In order to enable the automatic tracking of the laser spot with the laser tracker , one TV camera is attached at the end of the sighting tele-scope. Image signals detected by the TV camera are processed with an elabolate image processor , which gives the raster coordinates of the laser spot. Considering the azimuth, elevation of two transits and the deviation angle of the laser spot from the center of the sighting tele-scope , 3-dimensional coordinates of the target points can be determined. In order to realize an easy setting of the measuring systems one simplified calibration technique to establish the geometrical arrangement of two electrical transits is presented. Following our technique , the geometrical arrangement of two electrical transits can be established with accuracy.

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

2. 3-D Measuring System

The setup of the 3-dimensional measuring system is shown in Fig.1. The system may be briefly described as a laser spot projector which projects and scan a laser beam on the target body , a laser tracker which is controlled to detect the laser spot at the center of the sighting tele-scope , and a system controller which conbined the laser pointer and the laser tracker to build a distinguished 3-dimensional measuring system.

The laser projector is shown in Photo.1 . The laser emitting tube is mounted on the laser spot projector. A Helium-Neon laser at a wavelength of 632.8nm with 3mW is emitted and reflected with two mirrors so that the laser beam is projected along the lens centers of the laser spot projector. Two electrical transits (read-out absobute angle error is less than 1 second) are reconstructed to build the laser spot projector and the laser tracker,whose azimuth corner and elevation can be controlled with two step-motors which have harmonic-drive reduction mechanisms to reduce mechanical backlash.

As can be seen in Photo.2 ,at the end of sighting tele-scope of the laser tracker , one CCD TV camera is mounted to detect the laser spot on the target object.

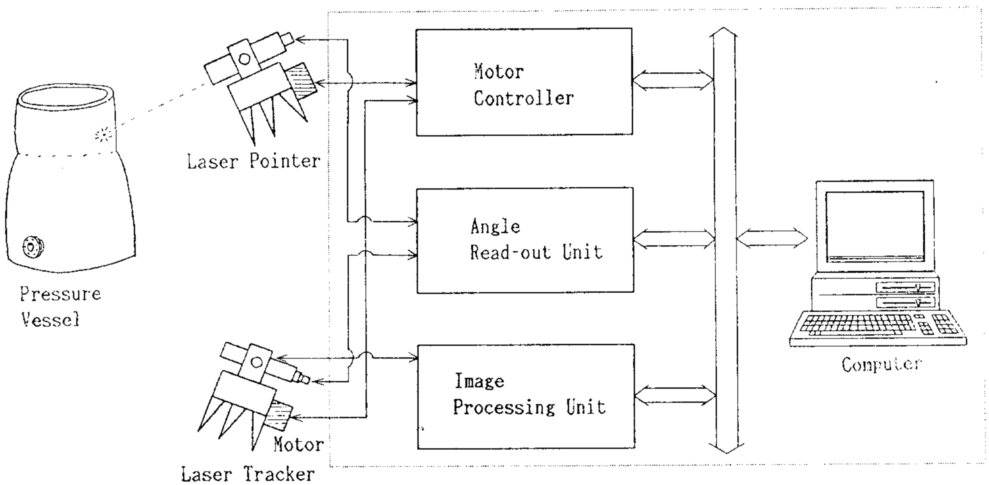

Fig.1 System Setup

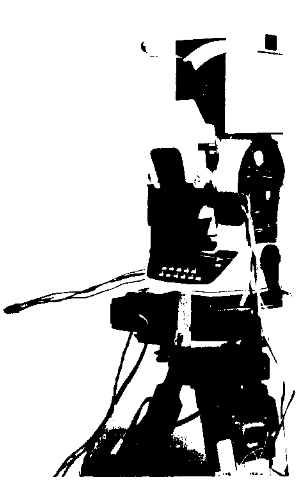

Photo.1 Laser Pointer

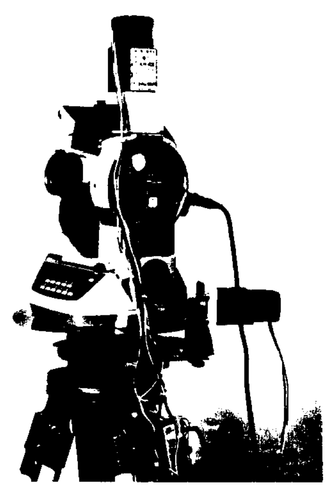

Photo.2 Laser Tracker

System Controller

The system controller is composed of 4 motor-controlling units which controlles 4 step-motors , 4 angle-read out units which read the azimuth and elevation angles of the laser spot projector and the laser tracker , and an image processing unit which processes the images obtained with the TV camera placed at the end of the laser tracker.

In order to cope with a variety of enviroments , the image processing units have functions to process eight bits of gray-scale images with 512×480 pixels per frame as well as binary images.

Consider the case of unfavorable lighting enviroments. Fast , the image processing unit stores two gray-scale images of the target points with and without the laser beam. Secondly , the image processing unit subtract one image from the other image so that the target point illuminated with the laser beam can be discriminated from its background. Finally , the image processing unit computes the raster coodinates of the center of gravity of the laser spot, using the subtructed image. Due to this gray-scale image processing , stable detection of the laser beam becomes possible.

A computer in the system controller reads all the azimuth and elevation angles with the angle-read-out units , and also read the raster coodinates of the laser beam spot with the image processing unit. Afterwards , the computer determines the 3-dimensional coodinates of the target point consideing the geometrical relation between the laser-spot projector and the laser tracker.

3. Determination of 3-dimensional coodinates

On determing the 3-dimensional coodinates of target points , the geometrical setup of the laser spot projector and the laser tracker should be calibrated in advance.

Calibration

Based on a minimum squared eror technique , measurements of six distinguished noncoplanar base points whose world coordinates are already known realize the caliblating process.[5] In the followings , the calibrating process of the laser spot projector is shown.

Let the world coordinates of the base point be xi , yi , zi and the corresponding azimuth and elevation angles be $\theta i, \phi i$. Since the relationship between the world coordinates and the azimuth and elevation angles-coordinates is essentially a perspective transformation , the following equation establishes ,

$$\lambda \begin{pmatrix} ui \\ vi \\ 1 \end{pmatrix} = \begin{pmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & 1 \end{pmatrix} \begin{pmatrix} xi \\ yi \\ xi \\ 1 \end{pmatrix} \tag{1}$$

where ui , vi represent $\tan\theta i$,$\tan\phi i$ respectively and elements hij represent the geometrical relationship between the above two coordinates.

Elimination of λ in Eq.(1) gives

$$\begin{pmatrix} xi & yi & zi & 1 & 0 & 0 & 0 & 0 & -uixi & -uiyi & -uizi \\ 0 & 0 & 0 & 0 & xi & yi & zi & 1 & -vixi & -viyi & -vizi \end{pmatrix} \times \begin{pmatrix} h_{11} \\ h_{12} \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ h_{33} \end{pmatrix} = \begin{pmatrix} ui \\ vi \end{pmatrix} \tag{2}$$

Therefore , for the six distinguished base points , Eq.(2) becomes

$$Th = w \tag{3}$$

where

$$T = \begin{pmatrix} x_1 & y_1 & z_1 & 1 & & & & & -u_1x_1 & -u_1y_1 & -u_1z_1 \\ x_2 & y_2 & z_2 & 1 & & 0 & & & -u_2x_2 & -u_2y_2 & -u_2z_2 \\ x_3 & y_3 & z_3 & 1 & & \cdot & & & & \cdot & \\ & \cdot & & & & \cdot & & & & \cdot & \\ & \cdot & & & & 0 & & & & \cdot & \\ x_6 & y_6 & z_6 & 1 & & & & & & & \\ & & & & x_1 & y_1 & z_1 & 1 & -v_1x_1 & -v_1y_1 & -v_1z_1 \\ & 0 & & & x_2 & y_2 & z_2 & 1 & -v_2x_2 & -v_2y_2 & -v_2z_2 \\ & \cdot & & & & \cdot & & & & \cdot & \\ & \cdot & & & & \cdot & & & & \cdot & \\ & \cdot & & & & \cdot & & & & \cdot & \\ & 0 & & & x_6 & y_6 & z_6 & 1 & -v_6x_6 & -v_6y_6 & -v_6z_6 \end{pmatrix}$$

$$h = \begin{pmatrix} h_{11} \\ h_{12} \\ \cdot \\ \cdot \\ \cdot \\ h_{33} \end{pmatrix} , \quad w = \begin{pmatrix} u_1 \\ u_2 \\ \cdot \\ \cdot \\ \cdot \\ u_6 \\ v_1 \\ v_2 \\ \cdot \\ \cdot \\ \cdot \\ v_6 \end{pmatrix}$$

Since the coefficient matrix T and the vector w in Eq.(3) is determined by the world coodinates and also the corresponding azimuth and elevation angles of the six base points , the vector h can be obtained as

$$h = (T'T)^{-1} T' w \quad (4)$$

where the matrix $(T'T)^{-1}T'$ is the pseud inverse of the matrix T .

Determination of 3-dimensional coordinates

Once calibrating vector h are oftained for the laser spot projector and the laser tracker , the 3-dimensional coordinates of target points can be determined as follows .

Rearrangement of Eq.(1) gives

$$A X = B \quad (5)$$

$$A = \begin{bmatrix} h_{31}u-h_{11} & h_{32}u-h_{12} & h_{33}u-h_{13} \\ h_{31}v-h_{21} & h_{32}v-h_{22} & h_{33}v-h_{23} \end{bmatrix}, \quad X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}, \quad B = \begin{bmatrix} h_{14}-u \\ h_{24}-v \end{bmatrix}$$

where x,y,z are coordinates of target points and u,v are tangent of azimuth θ and elevation ϕ.

Since Eq.(5) is valid for the laser tracker and also for the laser pointer , the following equation is obtained

$$\begin{bmatrix} Ap \\ At \end{bmatrix} X = \begin{bmatrix} Bp \\ Bt \end{bmatrix} \quad (6)$$

where Ap , Bp are the coefficients A ,B defined by Eq.(5) for the laser pointer , and At , Bt are the corresponding coefficients for the laser tracker.

Based on a minimum squared eror technique , it is widely acknowledged that the coordinates of the target point in Eq.(6) can be determined by

$$X = \left(\begin{bmatrix} Ap \\ At \end{bmatrix}' \begin{bmatrix} Ap \\ At \end{bmatrix} \right)^{-1} \begin{bmatrix} Ap \\ At \end{bmatrix}' \begin{bmatrix} Bp \\ Bt \end{bmatrix} \quad (7)$$

The coefficients matrix A and the vector B in Eq.(7) are determined by the read-out data from the laser pointer and the laser tracker.

It is important to note that Eq.(6) can be devided into four scalor equations

$$\begin{aligned} a(\theta p)'X &= b(\theta p) \\ a(\phi p)'X &= b(\phi p) \\ a(\theta t)'X &= b(\theta t) \\ a(\phi t)'X &= b(\phi t) \end{aligned} \quad (8)$$

where $\theta p, \phi p$ denotes azimuth and elevation angles for the laser pointer, $\theta p, \phi p$ denotes corresponding angles for the laser tracker. Three equations of Eq.(8) are enough to determine the 3-dimensional coordinates of the target point. Suppose the laser tracker is tracking the laser spot successfully , then the azimuth and elevation angles of the laser tracker are strongly correlated. In another words , the azimuth θt and elevation ϕt of the laser tracker are not mutually independent variables. When three angles θp , ϕp , θt are fixed at some values , the above three equations in Eq.(8) determines the coordinates X of the target point. Conversery , this coordinates determine ϕt by the fourth equation in Eq. (8). This means that once the laser pointer is set to one direction , the laser tracker needs to adjust the direction with only one degree of freedom.

4. Procedures of 3-d Measurement

The 16-bit computer (NEC PC9801 RA) controls all the data and determines the 3-dimensional coordinates of target points following the procedures in Fig.2 .

In order to increase the applicability of our system, target points are specified in the following two kinds of operation mode.

In the first operation mode (Semi-Auto mode) , the operator specifies all the movement of the laser beam using some input devices like a light-pen or a mouse-pointer. Of couse , the operator needs not to control the laser tracker , which automatically moves so that the laser spot is detected in the center of sighting tele-scope.

In the second operation mode (Full-Auto mode), the operator specifies only boundary of the target area using some input devices . Once the boundary of the target area are specified , the laser pointer automatically moves in this specified area and the laser tracker automatically tracks the laser beam on the target body.

It should be noted that the laser tracker may fail to detect the laser beam because of concavity or materials of the target. While the laser tracker tries to detect the target points considering the correlation between the azimuth and elevation angles of the laser tracker , some failures are inevitable. In the failed cases ,the computer omit this unsuccessful point and proceed to the next target point .

In order to increase the tracking speed of the laser tracker , a certain degree of deviation of the laser spot from the center of the sighting tele-scope is admitted. This becomes possible due to the modification of the azimuth and elevation angles of the laser tracker , considering the raster coordinates of the laser spot measured by the image processing unit.

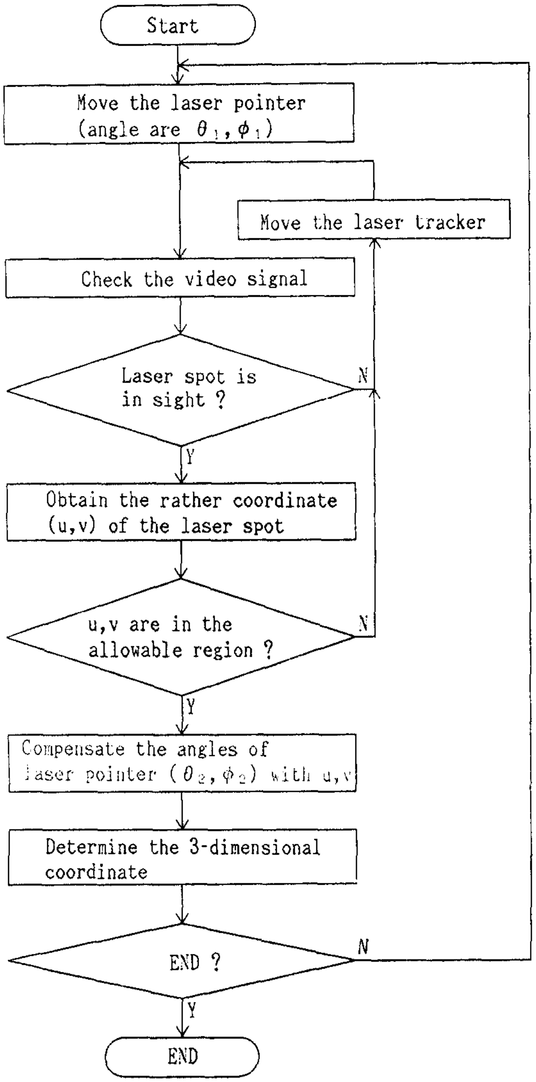

Fig.2 Flow Chart

5. Experiments

In order to test the utility of our system devoloped , two experimental measurements are executed. Photo.3 shows the target car (DAIHATSU Cuore) which was settled 8 meters away from the measuring system.

The laser tracker and the laser pointer were set 5 meters apart . Four hundreds of target points on one side of the target car were measured by the 3-dimensional measuring system presented here. This measurement took about 8 minutes.

In Photo.4 ,the target car is regenerated by the data obtained.

In Photo.5,one regenerated shape of another target car (TOYOTA Corolla) is presented ,where 1800 target

Photo.3 Target Car
(DAIHATSU Cuore)

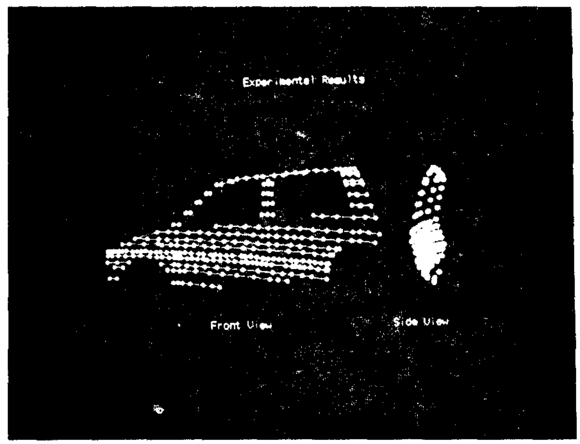

Photo.4 Experimental Result-1
(DAIHATSU Cuore)

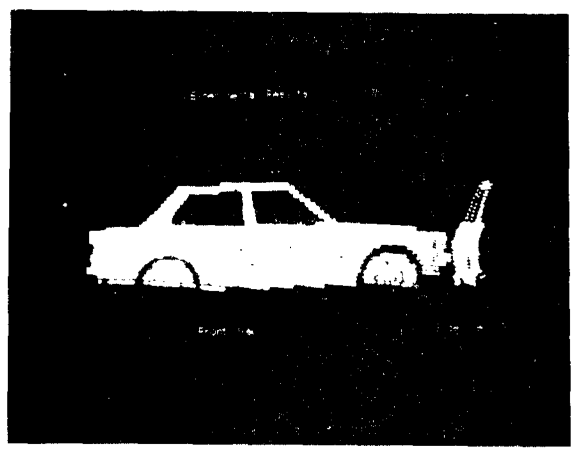

Photo.5 Experimental Result-2
(TOYOTA Corolla)

points are measured in 30 minutes . Experimental results show that maximum absolute errors in position were less than 1.0mm.

These experiments were executed outside on the cloudy day. While measurements were limited only on one side of cars , an employement of reflecting mirrors enables the measurement on another side and also on the top without moving the measuring system.[6] Of course , the posture of the mirror need to have been calibrated in advance.

This calibration of the mirror is easily executed by measuring the 3-dimensional positions of three points on the mirror using the 3-dimensional measuring system.

6. Conclusion

A 3-dimensional measuring system using two electrical transits for structures and pressure vessels has been developed. The 3-dimensional shape is measured by projecting a laser beam with a laser pointer and tracking the laser beam with a laser tracker. Triangulation is used to determine the location of sample points.

Among the features of the system is the employment of two electrical transits which enables 3-dimensional measurements of huge target bodies like structures and pressure vessels with high accuracy. Furthermore , the employment of an image processing unit realizes an automatic 3-dimensional measurement. A calibrating method presented provide a simple and efficient way of setting the 3-dimensional measuring system.

The feasibility of using the system for the practical applications has been demonstrated by measuring two cars.

Acknowledgement

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