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3D-Coordinate Measuring System for Transit Automated Collimating

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Abstract

A light-weight and high-precision automatic 3-dimensional shape measurement system was developed. The system comprises an optical surveying instrument that has a built-in CCD camera, an image processor and a notebook size personal computer. Flat reflective targets with a circle mark are placed offset from selected points on the measurement object such as a section of a large structure before site installation. The optical surveying instrument measures the distance and angle of each of the targets in a cyclic manner guided by design coordinate information of the object stored in the computer, and obtains image data. The image processor identifies the target marks and analyses the image data and the personal computer calculates the positions of the points on the object from the measured positions of the targets to compensate the offset amount. As a result of accuracy confirmation tests of the system at our plant, standard deviation of 3-dimensional coordinate figures of measurements repeated 12 times was less than 1 mm at a distance of 30 m.

1. Introduction

Transits with electro-optical distance meters (EDMs) are used to measure the dimensions and three-dimensional (3D) position coordinates of civil engineering facilities, buildings, and other large structures. Formerly, the surveyor viewed through the collimating lens, found the target mark for distance measurement, and aligned the crosshair intersection with the distance measurement mark. Recently, high-precision EDM fitted with CCD cameras came into use, allowing the target marks to be automatically sighted on through the image recognition of collimated figures from the images captured with the CCD camera. For the purpose of measuring the 3D shape of bridge members, the authors developed a system that automatically uses a motor-driven EDM equipped with a commercial CCD camera and special target marks, automatically sights the EDM on each of the target marks, and determines the 3D coordinates of the target marks by image processing. For the detail of the image processing logic adopted in the 3D coordinate measuring system, refer to Reference 1.

The new system measures and confirms the 3D coordinates of a given point on a large structure with a CCD camera-mounted EDM. That is, a collimating target mark is installed at a feature point, important point, or other point whose coordinates are to be determined. First, the line of sight of the EDM is brought to the point in question, 5 m - 20 m away from the observation point, based on the design coordinate data. Then, the image of the point is captured, and the distance and angle of the point are measured. The system is characteristic in that it can determine the 3D position coordinates of the center points of not only collimating marks but also other features,

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such as bolt holes whose center coordinates are invisible, by considering the tilt of the target surface if the relative coordinates (offset) from the collimating mark center are known.

The results of evaluation tests show that the system can now measure the x, y, and z coordinates of points at a distance of about 30 m to repeatability with standard deviations of less than 1.0 mm each.

The CCD camera-equipped EDM system is beginning to find use in surveying for building construction and measuring the 3D position coordinates of particular points on members of large structures like bridges. If it is capable enough to determine 3D position coordinates with precision of 1.0 mm over 30 m, it is expected to find use in a wider variety of applications.

2. Development History and Concepts

To meet the demand of owners to eliminate temporary assembly in the construction of bridges, Nippon Steel Corporation (NSC) started to study the introduction of EDM systems in fiscal 1993. In the spring of 1994, a surveying equipment manufacturer announced the development of an EDM equipped with a CCD camera. Assuming the use of the EDM, NSC started work on the development of an automatic measuring system on the basis of image recognition technology of the Electronics Research Laboratories (presently the Systems Research & Development Center, Electronics & Information Systems Division) in the summer of the same year, and demonstrated the practicability of the system with receipt of an EDM in February 1995. After various improvements, the system is now used in the 3D coordinate measurement of bridge members at NSC's Wakamatsu Fabrication Center.

The system was developed under the concepts of portable or easily relocatable measuring devices and systems with the functions of automatically turning an EDM-mounted transit on the basis of the design coordinates of large structures or parts, of automatically sighting on the targets installed at or offset from the measurement points on the members to be measured, of determining the 3D coordinates of the center of each target, and of estimating the 3D coordinates of the measurement points on the members.

3. Method for Estimating 3D Coordinates of Measurement Points

3.1 Principle of automatic collimation[2, 3]

A collimating target mark or a square reflective plate on which are drawn a circle and a line segment is installed at each of the points whose coordinates are to be measured on the structure to be measured. Using a transit with an electro-optical distance meter (EDM), or a telescope of a given magnification with a built-in CCD camera, from the observation point, the distance D from the collimation axis of the telescope to the intersection of the target mark, the horizontal angle Hp of the line of sight, and the vertical angle Vp of the line of sight are measured. At the same time, video image data are recorded (see **Fig. 1**).

The 3D shape of the structure to be measured is determined by obtaining the 3D coordinates T of the center of the target mark and the 3D position coordinates in the observation coordinate system of the coordinate point Q with the relative coordinates (h, f, d) in the mark coordinate system with the center of the mark as the origin.

1) 3D coordinates of center of target mark

The true-circle mark drawn on the reflective plate and imaged with the CCD camera is captured as an elliptic image if it has the collimation axis and angle of the CCD camera.

The deviations (Δx, Δy, Δz) of the center point of the target from

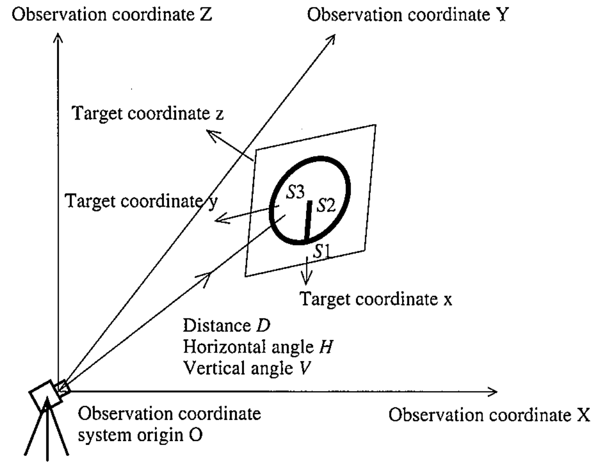

Fig. 1 Relationship between target coordinate system and observation coordinate system

the collimation point of the CCD camera are calculated from the video image data of the elliptic mark. The image coordinate system is established by letting zp be the collimation axis, xp-yp be the plane that orthogonally intersects the collimation axis zp, xp be the horizontal axis, and yp be the axis that orthogonally intersects the horizontal axis xp. The collimation point on the target or the point at which the collimation axis intersects the target is denoted by P and taken as the origin of the image coordinate system. The image of the target projected onto the plane xp-yp is analyzed to determine the deviations (Δx, Δy) of the center C of the target image from the collimation point P and the major axis a^* and minor axis b^* of the target image. The major axis a^* is always equal to the diameter of the true-circle target and is known. From the ratio of the major axis a^* to the minor axis b^*, the angle ϕ (angle of incidence) between the target surface 7 and the collimation axis is calculated by

$$\phi = \pm\, arc\,\sin\,(a^* / b^*) \quad (1)$$

Furthermore, the angle α between the longitudinal axis (axis L) and horizontal axis (axis xp) of the target is obtained. The deviation Δz of the target center point in the collimation axis is calculated by the following equation:

$$\Delta z = \sqrt{(x \times x + y \times y)} \times \sin\,(\alpha + arc\,\tan\,(\Delta x / \Delta y) / \tan\phi \quad (2)$$

Next, the method of calculating the coordinates of the target center point is described. When the EDM is taken as the origin O, the 3D coordinates (Xc, Yc, Zc) of the target center point T in the coordinate system are calculated by the following equation from the polar coordinates (D, Hp, Vp) of the collimation point P on the target surface and from the deviations (Δx, Δy, Δz) from the collimation point P in the image coordinate system:

$$\begin{pmatrix} Xc \\ Yc \\ Zc \end{pmatrix} = D \begin{pmatrix} \sin Vp \times \sin Hp \\ \sin Vp \times \cos Hp \\ \cos Vp \end{pmatrix} +$$

$$\begin{pmatrix} \cos Hp & \sin Hp \times \cos Vp & \sin Hp \times \sin Vp \\ -\sin Hp & \cos Hp \times \cos Vp & \cos Hp \times \sin Vp \\ 0 & \sin Vp & \cos Vp \end{pmatrix} \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \end{pmatrix} \quad (3)$$

Let h be the distance from the origin T to the measurement Q in the direction of the base line in the mark coordinate system where the target center T is the origin and the direction of the base line is the x-axis; f be the distance in the orthogonal direction of the target plane; d be the distance in the direction that orthogonally intersects the h-f plane; and β be the angle between the longitudinal axis (axis L) of the target image and the image of the base line. Then, the coordinate values (Δxs, Δys, Δzs) of the measurement point Q when the target center point T is the origin of the image coordinate system are given by the following equations. If

$$D = \sqrt{(\sin\phi \times \sin\phi + \tan\beta \times \tan\beta)} \tag{4}$$

then,

$$\begin{pmatrix}\Delta xs\\ \Delta ys\\ \Delta zs\end{pmatrix} = \begin{pmatrix}\cos\alpha & \sin\alpha & 0\\ -\sin\alpha & \cos\alpha & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}(h\times\sin\phi - f\times\tan\beta)/D\\ (h\times\sin\phi\times\tan\beta + f\times\sin\phi\times\sin\phi)/D - d\cos\phi\\ (h\times\cos\phi\times\tan\beta + f\times\cos\phi\times\sin\phi)/D + d\sin\phi\end{pmatrix} \tag{5}$$

When the coordinates of the above-mentioned measurement point Q in the image coordinate system are transformed to the corresponding values in the observation coordinate system, the 3D coordinate values (Xt, Yt, Zt) of the measurement point A with the EDM itself taken as the origin O is given by

$$\begin{pmatrix}Xt\\ Yt\\ Zt\end{pmatrix} = \begin{pmatrix}Xc\\ Yc\\ Zc\end{pmatrix} + \begin{pmatrix}\cos Hp & \sin Hp\times\cos Vp & \sin Hp\times\sin Vp\\ -\sin Hp & \cos Hp\times\cos Vp & \cos Hp\times\sin Vp\\ 0 & \sin Vp & \cos Vp\end{pmatrix} \begin{pmatrix}\Delta xs\\ \Delta ys\\ \Delta zs\end{pmatrix} \tag{6}$$

The 3D coordinates of the measurement point in the observation coordinate system, image coordinate system, and target coordinate system can be mathematically determined by the above equations. When the CCD camera is placed directly opposed to the target, the error of the angle of incidence ϕ (angle of inclination of the target surface) is increased by the constraint of the pixel count of the CCD camera. The error of the angle between the major axis of the ellipse obtained from image analysis and the base line causes the sign of tan β in Eq. (5) to be inverted when the minor axis of the ellipse is extremely close to the direction of the base line. For this reason, the method described below is adopted in the commercial system.

3.2 Automatic collimation method adopted in commercial system[4)]

Offset measurement is one feature of the developed system. The commercial system determines the vectors in the direction of the base line by measuring the distance and angle of three mark points on the target surface by the following procedure:

1) Calculate an approximate distance and horizontal and vertical angles to the target center. Orient the collimation axis in that direction, focus the EDM on the target, measure the distance and angle of the target, capture the mark image data, identify the ellipse, and determine the center position of the ellipse on the image.
2) From the equation of the ellipse of the mark image derived from the point sequence comprising the mark image, the equation of the half-line derived from the point sequence comprising the base line image and taking the mark center of the base line image as the base point, and the intersection of the ellipse and the line and the base line, determine the intersections of the half-line and the ellipse at angles of 90, 180, and 270°.
3) Bring the collimation axis to the three intersections on the circumference of the ellipse obtained as described in the step 2) above, and measure the distance and angle of each intersection. Transform the measured distance and angle data of the three intersections that do not lie on the same line to the corresponding orthogonal coordinates in the observation coordinate system. Obtain the transformation matrix for the target coordinate system and the observation coordinate system.
4) Transform the coordinates (h, f, d) of the target point Q in the target coordinate system to the corresponding 3D coordinates (Xt, Yt, Zt) in the observation coordinate system by using the transformation matrix of Eq. (5).

3.3 Method for estimating transformation matrix between target coordinate system and observation coordinate system

Assuming that the observation coordinate data $S1$ ($x1$, $y1$, $z1$), $S2$ ($x2$, $y2$, $z2$) and $S3$ ($x3$, $y3$, $z3$) of the three points that do not line on the same line on the collimation mark are obtained and that $S2$ and $S1$ are known to be the mark center coordinates and the coordinates of a point on the x-axis in the target coordinate system, respectively, the direction cosines of the axes o-x, o-y and o-z in the target coordinate system with the ellipse center position $S2$ as the origin o are obtained, and the transformation matrix is constructed for the target coordinate system and the observation coordinate system. For simplicity's sake, the $S2$ data are subtracted from the data of the three points, and the results are denoted again by $S1$, $S2$ and $S3$.

1) First, $S1$ ($x1$, $y1$, $z1$) are the 3D coordinates of the point defined as the intersection of the x-axis of the target coordinate system and the ellipse (circle). If

$$D1 = \sqrt{(x1\times x1 + y1\times y1 + z1\times z1)} \tag{7}$$

then the direction cosines ($l1$, $m1$, $n1$) of the axis o-x in the target coordinate system that correspond to the axis O-XYZ in the observation coordinate system are given by

$$l1 = x1 / D1 \tag{8}$$

$$m1 = y1 / D1 \tag{9}$$

$$n1 = z1 / D1 \tag{10}$$

2) Next, the x-axis of the target coordinate system orthogonally intersects the mark surface that is the plane o-xy. The plane that passes through the points $S1$, $S2$, and $S3$ on the mark surface are expressed by

$$\begin{vmatrix}X & Y & Z & 1\\ x1 & y1 & z1 & 1\\ x2 & y2 & z2 & 1\\ x3 & y3 & z3 & 1\end{vmatrix} = 0 \tag{11}$$

Rearranging yields

$$A\times X + B\times Y + C\times Z = 0 \tag{12}$$

If

$$D3 = \sqrt{(A\times A + B\times B + C\times C)} \tag{13}$$

the direction cosines ($l3$, $m3$, $n3$) of the z-axis are given by

$$l3 = A / D3 \tag{14}$$

$$m3 = B / D3 \tag{15}$$

$$n3 = C / D3 \tag{16}$$

3) Lastly, to obtain the direction cosines of the o-y-axis in the target coordinate system, the unknown coordinates of the intersection of the positive y-axis and the circle are denoted by ($x4$, $y4$, $z4$), and the radius of the circle on the actual mark is denoted by R. Since ($x4$, $y4$,

$z4$) are the coordinates of a point on the mark plane, the following equation holds:

$$A \times x4 + B \times y4 + C \times z4 = 0 \quad (17)$$

Since the radius of the circle on the actual mark is denoted by R,

$$x4 \times x4 + y4 \times y4 + z4 \times z4 = R \quad (18)$$

Since the x-axis (o→x) and the y-axis (o→y) orthogonally intersect each other in the actual space, the following equation holds:

$$x1 \times x4 + y1 \times y4 + z1 \times z4 = 0 \quad (19)$$

When Eqs. (17) to (19) are regarded as equations concerning ($x4$, $y4$, $z4$) and solved, finally,

$$x4 = R / \sqrt{(1 + a \times a + b \times b)} \quad (20)$$

$$y4 = a \times x4 \quad (21)$$

$$z4 = b \times x4 \quad (22)$$

where

$$a = (- A \times z1 + C \times x1) / \det \quad (23)$$

$$b = (- B \times x1 + A \times y1) / \det \quad (24)$$

If

$$D2 = \sqrt{(1 + a \times a + b \times b)} \quad (25)$$

then, the direction cosines ($l2$, $m2$, $n2$) of the oy-axis can be determined as follows:

$$l2 = 1 / D2 \quad (26)$$

$$m2 = a / D2 \quad (27)$$

$$n2 = b / D2 \quad (28)$$

4) If the origin o-xyz in the target coordinate system is (Xc, Yc, Zc) in the observation coordinate system, the transformation matrix becomes as follows:

$$\begin{pmatrix} X - Xc \\ Y - Yc \\ Z - Zc \end{pmatrix} = \begin{pmatrix} l1 & l2 & l3 \\ m1 & m2 & m3 \\ n1 & n2 & n3 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \quad (29)$$

The 3D coordinates (Xt, Yt, Zt) of the relative coordinate point Q with the offset values (h, f, d) with respect to the mark center can be calculated by the following equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} Xc \\ Yc \\ Zc \end{pmatrix} + \begin{pmatrix} l1 & l2 & l3 \\ m1 & m2 & m3 \\ n1 & n2 & n3 \end{pmatrix} \begin{pmatrix} h \\ f \\ d \end{pmatrix} \quad (30)$$

4. Functionality and Performance of Commercial System

4.1 Equipment configuration

The configuration of the system is shown in **Fig. 2.** The component ① is a motor-driven electro-optic distance meter (EDM) that contains a CCD camera in a 30× telescope. The EDM can measure distances and horizontal and vertical angles, record video image data, and adjust the collimation direction, focus, and illumination, among other things. The Sokkia Model MET-N2V EDM features a distance measurement accuracy of ±(0.5 + measurement distance × 10^{-6}) mm, angle measurement accuracy of ±2 sec, and stopping accuracy of ±5 sec/±15 sec (switchable).

The component ② is a Yokokawa ADS Model PIP-7000 image processing unit. It captures an image at a command from a computer, processes the image as described here, and outputs such data items as the mark center position coordinates, major axis, minor axis, and main axis direction angle.

The component ③ is a system control personal computer. It controls the EDM, and provides data integration, coordinate transformation, and operator interface.

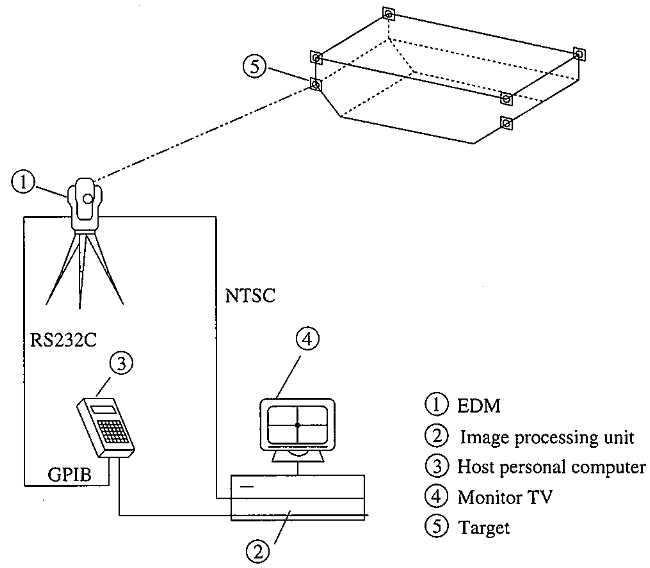

Fig. 2 3D coordinate measuring system

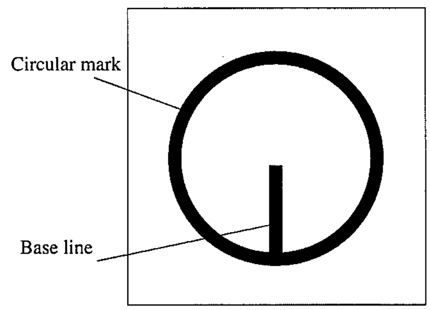

Fig. 3 Target with circular mark and base line

The component ④ is a monitor TV for viewing real-time video images from the EDM and processed images from the image-processing unit.

The component ⑤ is a reflective target. Its enlarged view is given in **Fig. 3**.

Images are transmitted between the EDM and the personal computer by the RS232C method, between the image processing unit and the personal computer by the GPIB method, and between the EDM, the image processing unit and the TV by the NTSC method. Of the images discussed above, the mark images captured at commands from the personal computer are mainly processed by the software of the image-processing unit. Processing of the images concerned with the estimation of 3D coordinates is achieved as a function of the host personal computer.

4.2 Automatic measurement procedure

The 3D coordinate measuring system automatically cycles and sights on targets installed on the object to be measured according to their design 3D coordinates, and calculates the 3D coordinates of the measurement points in the coordinate system of the object to be measured. This operational flow is described below.

1) Enter in the control personal computer the 3D coordinates of the center of the target ⑤ (hereinafter referred to as the target coordinates) prepared for the design or measurement of the structure to

be measured and the offset values of the target ⑤.

2) Set up the EDM at the observation point, and manually sight the EDM on one point on one of the three targets installed on the structure to be measured but not lying on the same line (measure the distance and angle of the selected point). Once the coordinate system is established as basis for measurement after another automatic collimation, the remaining target coordinates are transformed.
3) The host personal computer controls the EDM according to the target coordinates transformed in the step 2) above. The EDM is automatically turned for the number of targets installed and is automatically sighted on each target as described in Section 3.2. The coordinates of the mark center of each target and the 3D coordinates of each measurement point (offset point) are calculated. These coordinates are subsequently displayed and stored in the control personal computer.

4.3 Accuracy of estimating 3D position coordinates of targets

Six targets were installed, numbered 1 to 6 from the farthest to the closest ones and not lying on the same line on wall columns and other members inside of a factory. The transit was set up about 6 m from the target 6 and used to measure the coordinates of the targets experimentally. The linear distance was about 7 m to the target 6 closest to the observation point and about 30 m to the target 1 (with an offset value of 50 mm) farthest from the observation point. Of the six targets, the targets 1, 3, and 6 were used as control standards. The 3D coordinates of the mark center points of the three targets are manually measured and used to prepare the transformation matrix between the observation system and the CAD system.

Once the transformation matrix is created, these control points become part of the general points whose 3D coordinates should be measured. The measurement experiment was conducted by automatically turning the EDM. More specifically, a turn route was established in the order of targets 2 → 4 → 5 → 1 → 3 → 6 → 2 ···, and this route was repeated 12 times to obtain the 3D position coordinates of each target center P and offset Q. The same target was not continuously measured 12 times, but in 12 turn passes.

The system is designed to achieve a measurement accuracy of within 1 mm for the distance of 30 m = 30,000 mm. Since this ex-

Table 1 3D coordinate measurement results

Term		Target center	Measurement point (offset point)
Distance to targer 1		3,897.7 mm	3,897.7 mm
Standard deviation of distance	(mm)	0.10	0.10
Mean coordinates (*x*, *y*, *z*)	(mm)	(26,964.0, 0.21, 659.5)	(26,963.9, 7.0, 646.0)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.04, 0.12, 0.11)	(0.14, 0.15, 0.12)
Base line angle	(deg)	–	85.03
Standard deviation of base line angle	(deg)	–	0.23
Distance to targer 2		4,633.7 mm	4,624.5 mm
Standard deviation of distance	(mm)	0.10	0.23
Mean coordinates (*x*, *y*, *z*)	(mm)	(22,493.0, 643.0, –376.0)	(22,493.5, 634.0, –358.2)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.08, 0.15, 0.11)	(0.18, 0.21, 0.14)
Base line angle	(deg)	–	266.8
Standard deviation of base line angle	(deg)	–	0.19
Distance to targer 3		13,404.4 mm	13,405.8 mm
Standard deviation of distance	(mm)	0.12	0.41
Mean coordinates (*x*, *y*, *z*)	(mm)	(13,581.0, –18.0, –104.0)	(13,580.6, –2.6, –129.8)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.13, 0.16, 0.20)	(0.35, 0.34, 0.24)
Base line angle	(deg)	–	91.08
Standard deviation of base line angle	(deg)	–	0.62
Distance to targer 4		17,965.4 mm	17,966.0mm
Standard deviation of distance	(mm)	0.15	0.27
Mean coordinates (*x*, *y*, *z*)	(mm)	(9,010.5, 1.08, –0.53)	(9,011.17, 24.8, –44.56)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.14, 0.17, 0.18)	(0.23, 0.33, 0.25)
Base line angle	(deg)	–	89.26
Standard deviation of base line angle	(deg)	–	0.40
Distance to targer 5		22,391.7 mm	22,394.9 mm
Standard deviation of distance	(mm)	0.19	0.59
Mean coordinates (*x*, *y*, *z*)	(mm)	(4,579.4, –105.0, 95.17)	(4,577.09, –82.0, 50.9)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.19, 0.30, 0.37)	(0.65, 0.77, 0.45)
Base line angle	(deg)	–	89.01
Standard deviation of base line angle	(deg)	–	0.89
Distance to targer 6		26,971.5 mm	26,972.1 mm
Standard deviation of distance	(mm)	0.11	0.25
Mean coordinates (*x*, *y*, *z*)	(mm)	(0.43, –0.40, –0.93)	(0.21, –44.0, –24.7)
Standard deviations of coordinates (*x*, *y*, *z*)	(mm)	(0.12, 0.33, 0.41)	(0.21, 0.38, 0.71)
Base line angle	(deg)	–	359.5
Standard deviation of base line angle	(deg)	–	0.59

Note 1: Means and standard deviations are those of data measured along predetermined route 12 times.

Note 2: Distance to target is linear distance from observation point to mean coordinates of center of target.

Note 3: Standard deviations of center coordinates are standard deviations of x-, y-, and z-coordinates.

perimental work was not able to utilize another method capable of obtaining 3D position coordinates to an accuracy of within 1 mm in the distance range of 2 to 30 m, the correct 3D position coordinates of each target center and offset point are not known. As the next best method, a given point was measured by the system many times, and the accuracy of estimating 3D position coordinates was evaluated according to the repeatability of the measurements thus taken. **Table 1** presents the measurement data of the target points.

4.4 Functions added to commercial system

When the system was commercialized, it had offset measurement and other functions added as described below.

1) Offset measurement

A target is installed offset from a measurement point on an object to be measured, the distance and angle of a point on the target are measured, and the 3D coordinates of the measurement point are automatically calculated from the distance and angle measurements. In other words, the 3D coordinates of the point at which the target is installed (measurement point on the object to be measured) can be obtained by simply sighting on the target.

2) Automatic measurement

A target is imaged with the CCD camera, and the image thus acquired is analyzed. The target is automatically sighted on according to the results of the image analysis. The center of the target, the inclination of the collimation plane, and the base line angle are determined and used to perform offset measurement.

3) Manual measurement

The target imaged with the CCD camera is directly viewed and manually sighted on. The center of the target, the inclination of the collimation plane, and the base line angle are determined to perform offset measurement. The system can also carry out offset measurement with the EDM and the personal computer.

4) Offline teaching

The 3D design coordinate values of the measurement point on the object to be measured as required for the control of the EDM are created beforehand with a modeling system or 3D CAD system, for example.

5) Online teaching

The 3D design coordinate values of the measurement point on the object to be measured as required for the control of the EDM are created by directly sighting the EDM on the target.

6) Automatic turning

Based on the position (3D coordinate values) of the target determined by offline or online teaching, the drive motor of the EDM is controlled so that the EDM can be automatically oriented in the specified direction of the target.

7) Wireless remote control

The personal computer communicates with and controls the EDM through a radio modem (RS-232C).

8) Real-time presentation

Measured values of individual targets, such as their center point, measurement point and base line angle, and deviations from design values are sequentially presented on the display of the personal computer, so that the shape and error of the object measured, target installation mistake, and success or failure of image processing can be known in real time.

9) Re-measurement

For a target whose measurement failed or target not measured for some reason, another automatic or manual measurement is made by changing image processing parameters and measurement conditions like illumination.

5. Discussion

5.1 Target mark figures

1) A cross figure, for example, was sufficient for conventional visual collimation because it was satisfactory if the surveyor could recognize the measurement point as such. Automatic recognition with image data calls for such a figure as to allow the measurement point to be specified as such and to be easy to recognize for image processing. Under one frequently used method, a square reflective target, for example, is used and recognized as a square (generally, as a parallelogram), and its center of gravity of area is determined. This method is acceptable if the center alone of the target is to be determined. When the coordinates of a point as offset with respect to the center and plane of the target are to be estimated, it is necessary to find the transformation matrix that takes the inclination of the plane into account. This requirement is difficult to meet by the center-of-gravity-of-area method for simple figures.
2) Therefore, a circle was selected as a simple and mathematically easy-to-use target mark and the center of said circle was considered the center of the target. The circle drawn on the plane of the surface generally looks like an ellipse. The degree to which the circle looks like an ellipse is the information that indicates the degree of inclination of the target surface. If the circular or elliptic target figure is not completely visible (or detectable), it can be determined to be an ellipse from its partial view. A robust estimation is thus possible.
3) The transformation matrix between the target coordinate system and the observation coordinate system is required to enable the estimation of not only the 3D coordinates of the center point of the target figure but also the 3D position coordinates of a point with specified offset. To establish this relationship, a base line that represents the x-axis of the target coordinate system was introduced.

5.2 Offset calculation from image data

1) The base line was introduced to perform offset calculation from target image data. The method of sequentially transforming the offset coordinates (differences between the coordinates of the mark center point and the coordinates of the measurement point) from the target coordinate system to the image coordinate system to the observation coordinate system includes the function tan β with a particular point in the transformation equation from the target coordinate system to the image coordinate system. When the minor axis of the ellipse is brought extremely close to the base line direction by the error between the major axis of the ellipse and the base line angle as determined by image analysis, the sign of tan β is inverted. Consequently, there develops an unstable region in the offset calculation results.
2) When the collimation axis is positively opposed to the target, the constraint of the pixel count of the CCD camera makes the difference in length (pixel count) between the major and minor axes of the ellipse extremely small, and increases the variability of error in the angle of incidence ϕ (angle of inclination of the target surface). This does not pose any problem with the estimation of the mark center coordinates, but produces an error that cannot be ignored in the calculation of the offset coordinate values.
3) The method adopted to solve the problems discussed in Items 1) and 2) above consists of automatically sighting on three points in the target plane (one point on the base line), finding the direction cosines of the target coordinate system with respect to the observation coordinate system, and directly determining the 3D offset

of the measurement point.

5.3 3D coordinate estimation accuracy

1) Discussion of 3D position estimation accuracy has the principal problem of "absence of accurate values to compare with". The distance measurement accuracy of the laser transit is guaranteed to be ±0.6 mm over 40 m. The direction angle resolution is within 2" of angle (or within ±0.4 mm over 40 m). The standard deviation is 0.66 mm over 25.5 m where reproducibility is somewhat large in variation with respect to the target center as shown in **Table 1**. These performance data indicate that the developed method and system are fully practicable.
2) The feasibility of measuring 3D coordinates with an accuracy of 1 mm or less up to 30 m is judged to have been demonstrated. To make this potential true, we think it imperative to establish the traceability of the 3D coordinate measuring system in link with an appropriate calibration system as soon as possible.

5.4 Validity of offset measurement

Adopting the offset measurement function of sighting on a target where a circle and base line mark are drawn made it possible to estimate the 3D coordinate values of the measurement point on the object to be measured without assuming the installation direction of the target. This means that the 3D shape of the object to be measured can be determined by simply sighting on specific targets. In offset measurement, it is necessary to measure the distance and angle of each target at least three times. The measurement time increases, but the required number of measurement points can be reduced. When measurements are taken in two or more directions, it is not necessary to replace coordinate transfer points. The measurement results of the measurement points can be obtained in real time. In this way, 3D coordinate measurements can be made with very high efficiency.

5.5 Size reduction of measuring system

Sharp improvement in the performance of personal computers in recent years has made it possible to replace the conventional processing work of the image-processing unit by a personal computer. If images are introduced through a video capture card (PCMCIA) and processed by a control personal computer, an automatic 3D coordinate measuring system can be composed of a electro-optical distance meter (EDM) and a notebook personal computer. In other words, the 3D coordinate measuring system can be made more compact.

6. Conclusions

1) The method discussed above can use the image data of a circle drawn on a target mark plate to identify the elliptic shape and to determine the center coordinates, major axis, minor axis and major axis angle of the ellipse with high accuracy.
2) As a result of the method noted in 2) above, a 3D coordinate measuring system was constructed in combination with a CCD camera-equipped laser transit system. The new system can measure 3D x-, y-, and z-coordinates with a standard deviation of less than 1 mm each by automatically turning the laser transit along a predetermined route 12 times for distances up to 30 m.
3) After various improvements, the system now can extract the target mark region, and can practically recognize the elliptical shape of the target mark with artificial illumination and without backlight outdoors. When made more compact, it will find more usage in surveying, civil engineering, building construction, determination of the shape and measurement of position coordinates of large structures.

References

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