A Study for Producing 3D Model Space from 2D Digital Picture using Photogrammetry Technology

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Abstract: Three-dimensional CAD and CG, which make use of advanced computer technology, has lately attracted considerable attention. Also attracting attention is photogrammetric technology to acquire three-dimensional coordinate data from two-dimensional image data recorded by digital cameras. Photographing and the determination of measuring points are more difficult even for experts in ground photogrammetry, for which the demand is increasing, as compared with the same tasks in aerial photogrammetry which is used for the preparation of maps and so on. Accordingly it takes enormous labor and time to obtain accurate three-dimensional coordinate data by ground photogrammetry and, therefore, it has hardly been put to practical use yet. Under the circumstances, the object of the present study was to develop a system which enables us, without requiring expensive apparatuses or expertise, to create 3D model spaces easily and quickly just by taking two-dimensional digital photographs.

Keywords: Photogrammetry, Digital Camera, 2D Digital Image, Optimal Pass Point, Genetic Algorithm, 3D Model, and Computer Graphics

1. Introduction

As information apparatuses progress, more and more digital data are used in various fields. The digitization of information is supported by not only the technological revolution of information apparatuses but also software which performs the work that we have been doing with analog apparatuses so far. Devised in the present study under the circumstances was algorithm which enabled the surveying of close subjects, or so-called ground photogrammetry. Another object of the present study was to develop a system which enabled us, without requiring expensive apparatuses or expertise, to create 3D model spaces easily and quickly just by taking two-dimensional digital photographs.

2. Outline of System

Aerial photogrammetry has so advanced that a point on the ground can be pinpointed with an error of about 1/5,000 of the flight height. However, it is difficult to obtain accurate three-dimensional coordinate data just by applying aerial photogrammetric technology to ground photogrammetry because the depth of field is large in ground photogrammetry. Accordingly, devised in the present study based on the photogrammetric technology systematized in the references 1) to 3) was a method of holding down the errors in measuring the depth of field by determining optimal pass points (measuring points) automatically.

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3. Digital Photogrammetry

The system developed in this study was based on "collinearity" that light reflected from a subject goes straight through the center of the lenses of a camera to make a reflection of the subject on a planar film and "coplanarity" that two centers of projection and the reflection of a subject are contained in the same plane. To be concrete, three-dimensional coordinate data were calculated by a coplanarity-based method of connecting two centers of projection. Coplanarity is described systematically in the reference 1). The method is illustrated in Fig.1 Digital photogrammetry [4] consists of three phases of inner orientation, relative orientation, and absolute orientation. Fig.2 shows the process of digital photogrammetry.

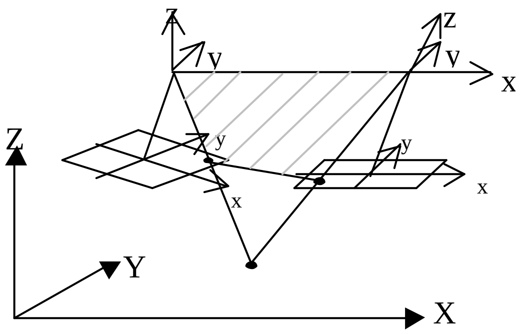

Fig.1 Method of Connecting Two Projection Centers Based on Coplanarity

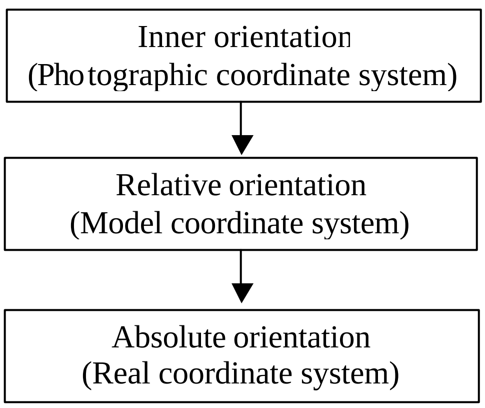

Fig.2 Process of Digital Photogrammetry

3.1 Inner Orientation

In the phase of inner orientation, factors, which arise from mechanical errors, refraction by lenses, etc. to disturb collinearityb [5), 6)], are removed. Then, coordinates in a coordinate system measured by image-editing software are transformed by affine transformation to coordinates in photographic coordinate system, of which the origin is set at the center of the photograph. In this study, the strain of films and coordinate axes were not considered because digital cameras were used. Accordingly corrected in this study were only skew strain, the scale, and movement of the origin, which can be corrected by affine transformation. The formula of affine transformation used in this study is as follows.

$$\begin{aligned} x' &= ax + by + c \\ y' &= dx + ey + f \end{aligned} \qquad (1)$$

3.2 Relative Orientation

Calculated by the method of connecting the two centers of projection in the phase of relative orientation are the locations of lens centers (B_{x1}, B_{y1}, B_{z1}) and (B_{x2}, B_{y2}, B_{z2}) and the angles of inclination of the two cameras ($\omega 1$, $\kappa 1$, $\phi 1$) and ($\omega 2$, $\kappa 2$, $\phi 2$) at the time when the left and right photographs were taken. Then the three-dimensional coordinate data on the subject are calculated by using the locations of lens centers and the angles of inclination of the cameras. The three-dimensional coordinate data thus calculated are relative model coordinates, the left center of projection being the origin, the distance between the right and left centers of projection being "1".

3.3 Absolute Orientation

In the phase of absolute orientation, the relative there-dimensional coordinate data calculated in the relative orientation are transformed into data in a real coordinate system of the scale of the real world.

Because aerial cameras for wide range photographing are generally used in aerial photography, correction for the curvature of the earth is made. In this study, however, the correction was not considered because ordinary digital cameras available on the market were used.

4. Development and Verification of System

4.1 Analysis by Conventional Photogrammetry

In photogrammetry, it is difficult to obtain accurate three-dimensional coordinate data by using only control points and measuring points (measuring pass points) for measuring distances. To obtain accurate three-dimensional coordinate data, it is necessary to set pass points (optional pass points) in balance through the photograph optionally. By using two photographs as shown in Fig.3 and setting nine optional pass points in balance, the subject was measured in accordance the procedure in Section 3. As the result, inaccurate three-dimensional data shown in Table 1 were obtained. Accordingly, keeping it in mind that multiple pass points do not raise the accuracy, the authors devised a method of reducing the error in measuring the depth of field by choosing optimal ones among multiple pass points.

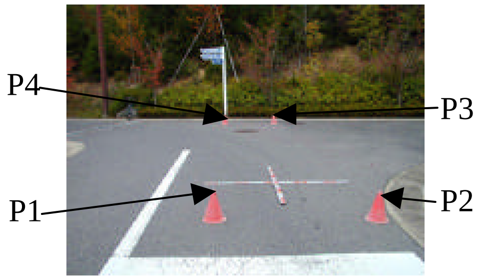

Photo taken from left


Photo taken from right

Fig.3 Ground Photogrammetry

Table 1 Result of Analysis by Conventional Photogrammetry

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.66	1.55232	-0.10768	-6.48684
P2 and P3	9.15	2.57675	-6.57325	-71.83879
P3 and P4	1.63	0.77108	-0.85892	-52.69463
P4 and P1	9.12	2.35296	6.76704	74.19999

4.2 Analysis by All-Solution Search

4.2.1 Outline of All-Solution Search

It is not easy even for experts to choose optimal ones among multiple pass points. Accordingly, devised in this study was a method of choosing optimal ones among ten optional pass points or so automatically (Fig.4).

As shown in Fig.4, the specifications of the cameras such as the focal distance and the number of pixels are inputted, and the coordinates of the four corners (fiducial marks) are calculated. The coordinates of the control points and the pass points are measured by image-editing software, and affine-transformed by using the measured coordinates of fiducial marks. Then relative orientation and the absolute orientation are made to calculate three-dimensional coordinate data. By using the residuals of the control points in the obtained three-dimensional coordinate data, an optimal combination of optional pass points is determined.

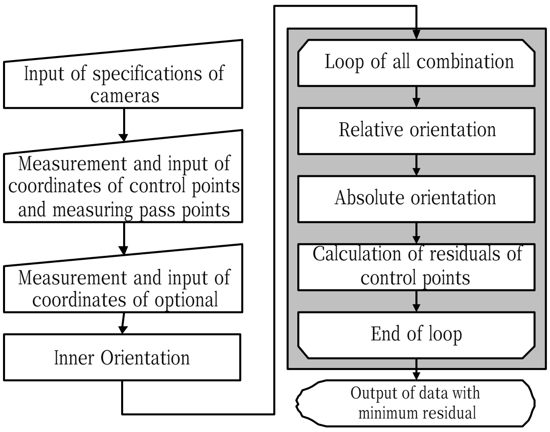

Fig.4 Process of All-Solution Search

4.2.2 Setting of Optional Pass Points

In the system developed in this study, ten optional pass points or so are set and an optimal combination of optional pass points is determined. First, an optional pass point is set at each corner of each photograph. If any corner has a control or measuring pass point in it, no optional pass point is set at the corner. Second, an optional pass point is set at the middle point between corners of each photograph. If a control or measuring pass point is set at any such middle point, no optional pass point is set there. Then 10 more optional pass points or so are set, the spots of control and measuring pass points avoided.

4.2.3 Result of Analysis

By using the photographs of Fig.3, nine optional pass points were set and the system chose optimal pass points automatically. Table 2 shows the result of the measurement made by using the optimal pass points. As shown in the table, accurate three-dimensional coordinate data were obtained with as small a mean error as a few percent.

In this system, however, when the number of optional pass points in "n," an optimal combination is chosen among "2^n-1" combinations. Accordingly, when the subject is a ball or a curved surface which requires a large number of pass points, the calculation takes enormous time. Therefore a method of hastening the search for an optimal solution was devised.

Table 2 Result of Analysis by Photogrammetry with All-Solution Search

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.66	1.74311	0.08311	5.00639
P2 and P3	9.15	9.19218	0.04218	0.46101
P3 and P4	1.63	1.72057	0.09057	5.55665
P4 and P1	9.12	8.90323	0.21677	2.37690

4.3 Determination of Pass Points by using GA

Genetic algorithm suitable to nonlinear combinatorial problems[7)] was used to determine optimal pass points. With this method, not optimal, but sub-optimal solutions can be calculated quickly. Ten optional pass points or so are set. Both measuring and optional pass points are used and they are treated as one individual. The process of choice, crossing, and mutation is repeated to find a sub-optimal solution. The vertical parallaxes calculated by relative orientation and the residuals of control points calculated by absolute orientation are used as objective functions which are evaluation. Then, by using the coordinates of lens centers and the angles of inclination of the cameras calculated based on the sub-optimal pass points, the three-dimensional coordinate data on the measuring pass points are calculated. Fig.5 shows the process (add the first four steps shown in Fig.4 to the top of the process.)

In this study, three-dimensional coordinate data as accurate as those obtained by all-solution search could be obtained quickly by using GA in determining pass points.

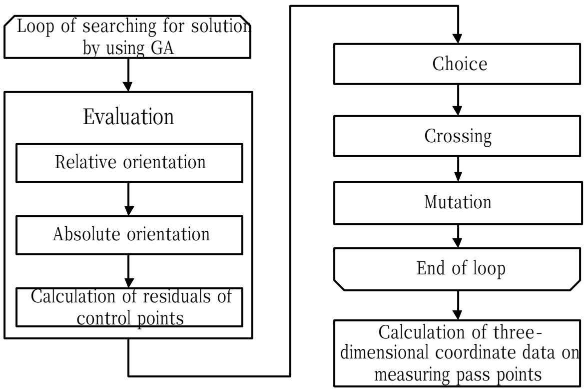

Fig.5 Determination of Pass Points by using GA

5. Translating Function of 3D Model

In this study, the VRML was used as a means to visualize three-dimensional coordinate data. The VRML is a standard language of ISO, which enables us to share information through the Internet. The translating function is to model the subject by using its three-dimensional coordinates data calculated by photogrammetric technology. The three-dimensional coordinates data on a subject are an aggregate of data on points. Accordingly developed in this study was an interface with the function of a translator to transform the file format of such three-dimensional coordinate data into the file format which the VRML could handle. With this function, the three-dimensional coordinate data groups of a subject are classified into the constituents of its surface model.

6. Verifying Experiments

Experiments were carried out to ascertain the accuracy of the system under different photographing methods, the performance of the system in acquiring the shapes of subjects, and the applicability of the system to CG modeling.

6.1 Photographing Methods and Accuracy

In this experiment, convergent photographing and parallel photographing were discussed and the absolute accuracy of the system was ascertained by fixing the height and the angles of inclination of the cameras with tripods and changing the distance between the subject and the cameras.

6.1.1 Convergent Photographing

Convergent photographing was made at the distances of 7.5 m (Fig.6), 12.5m, and 17.5 m, the axes of the two cameras intersecting with each other at an angle of approximately 55°.

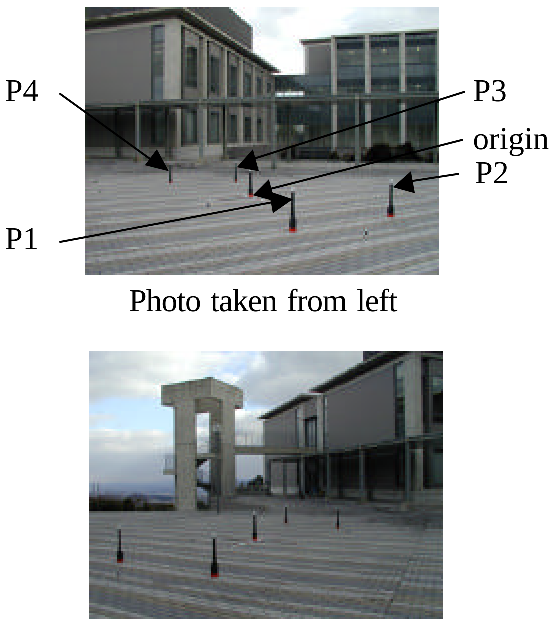

Photo taken from left

Photo taken from right

Fig.6 Convergent Photographing

(1) Photographing Distance: 7.5 m

Two photographs (Fig.6) were taken with two cameras at the distance of 7.5 m and eight measuring pass points and nine optional ones were set. The all-solution search system was applied to the analysis. Five optional pass points were chosen. As shown in Table 3, the accuracy in estimating the distances between measuring pass points was low.

Table 3 Result of Analysis (7.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	1.31478	-0.48522	-26.95650
P2 and P3	5.97	5.15146	-0.81854	-13.71081
P3 and P4	1.89	2.16945	0.27945	14.78590
P4 and P1	6.55	6.08174	0.46826	7.14907

(2) Photographing Distance: 12.5 m

Two photographs were taken with two cameras at the distance of 12.5 m and eight measuring pass points and nine optional ones were set. The all-solution search system was applied to the analysis. Four optional pass points were chosen. As shown in Table 4, no improvement of the accuracy took place as compared with the accuracy in the case of 7.5 m.

Table 4 Result of Analysis (12.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	1.56164	-0.23836	-13.24224
P2 and P3	5.97	7.01490	1.04490	17.50250
P3 and P4	1.89	2.57623	0.68623	36.30864
P4 and P1	6.55	8.13889	1.58889	24.25794

(3) Photographing Distance: 17.5 m

Two photographs were taken with two cameras at the distance of 17.5 m and eight measuring pass points and nine optional ones were set. The all-solution search system was applied to the analysis. Three optional pass points were chosen. As shown in Table 5, the accuracy fell as compared with the accuracy in the cases of 7.5 m and 12.5 m.

The reason of the lowest accuracy would be that because the photographing distance was longest, each pixel was obliged to accommodate the data on the largest area and hence the accuracy in recognizing the coordinates of the pass points fell.

Table 5 Result of Analysis (17.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	2.54167	0.74167	41.20408
P2 and P3	5.97	4.10853	-1.86147	-31.18035
P3 and P4	1.89	1.93745	0.04745	2.51059
P4 and P1	6.55	4.22325	2.32675	35.52292

6.1.2 Parallel Photographing

Parallel photographing was made at the distances of 7.5 m (Fig.7), 12.5m, and 17.5 m.

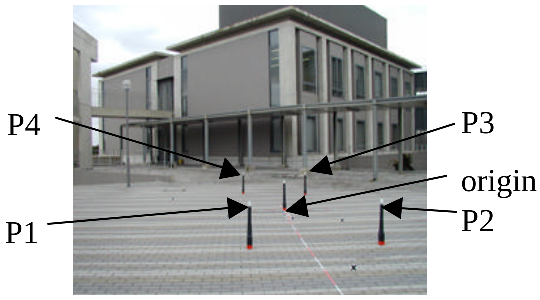

Photo taken from left

Photo taken from right

Fig.7 Parallel Photographing

(1) Photographing Distance: 7.5 m

Two photographs (Fig.7) were taken with two cameras at the distance of 7.5 m and eight measuring pass points and nine optional ones were set. The all-solution search system was applied to the analysis. Three optional pass points were chosen. As shown in Table 6, the accuracy in estimating the distances between measuring pass points was very high. Thus, highly accurate three-dimensional coordinate data were obtained.

Table 6 Result of Analysis (7.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	1.79569	-0.00431	-0.23955
P2 and P3	5.97	5.94482	-0.02518	-0.42183
P3 and P4	1.89	1.97264	0.08264	4.37244
P4 and P1	6.55	6.54680	0.00320	0.04882

(2) Photographing Distance: 12.5 m

Two photographs were taken with two cameras at the distance of 12.5 m and eight measuring pass points and nine optional ones were set. The all-solution search system was applied to the analysis. Five optional pass points were chosen. As shown in Table 7, the accuracy in estimating the distances between measuring pass points was high.

Table 7 Result of Analysis (12.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	1.79778	-0.00222	-0.12332
P2 and P3	5.97	6.05982	0.08982	1.50451
P3 and P4	1.89	1.96973	0.07973	4.21860
P4 and P1	6.55	6.63595	0.08595	1.31218

(3) Photographing Distance: 17.5 m

Two photographs were taken with two cameras at the distance of 17.5 m and eight measuring pass points and ten optional ones were set. The all-solution search system was applied to the analysis. Four optional pass points were chosen. As shown in Table 8, the accuracy fell as compared with the accuracy in the cases of 7.5 m and 12.5 m.

The reason of the lowest accuracy would be that because the photographing distance was longest, each pixel was obliged to accommodate the data on the largest area and hence the accuracy in recognizing the coordinates of the pass points fell.

Table 8 Result of Analysis (17.5 m)

Between measuring pass points	Measured value (m)	Calculated value (m)	Error (m)	Relative error (%)
P1 and P2	1.80	1.78335	-0.01665	-0.92502
P2 and P3	5.97	6.55657	0.58657	9.82530
P3 and P4	1.89	2.01957	0.12957	6.85576
P4 and P1	6.55	7.07733	0.52733	8.05084

6.1.3 Discussion

With convergent photographing, the distance between two points could be calculated with an error within about ± 1 m, which was smaller than the error of conventional ground photogrammetry thanks to the all-solution search system. However, ground photogrammetry with convergent photographing is not suitable for surveying which requires high accuracy or 3D modeling.

With parallel photographing, the distance between two points could be calculated with an error within about ± 10 cm. Thus ground photogrammetry with parallel photographing is suitable for information-processing work such as surveying which requires high accuracy and 3D modeling.

Regarding photographing distance, good results were obtained when it was 15 m or less in the case of the cameras (2,110,000 pixels) used in this study. However, such relation between photographing distance and the accuracy of coordinate data on measuring pass points depends on the specifications or performance of cameras such as the number of pixels and the quality of lenses.

6.2 Acquisition of Shapes of Subjects

In this experiment, the system was tested for its capability of acquiring the shape of the subject.

6.2.1 Photographing Method

As shown in Fig.8, photographs of the subject of a bottle were taken by parallel photographing in four directions at 90° intervals. When cameras were directed to each circumferential quarter section of the bottle surface, pass points in the right and left quarter sections were caught in the vision of the cameras.

6.2.2 Arrangement of Control Points

As shown in Fig.8, four wires were hung at 90° intervals around the bottle, each wire bearing four marks, or control points. Each wire has its own color, red (R), green (G), yellow (Y), or black (B) for its marks. The coordinate system was defined by treating the red bottom control point R1 as (0, 0, 0) and the coordinates of the other control points were measured as shown in Table 9. 220 round seals, each 5 mm in diameter, were attached on the bottle as measuring pass points.

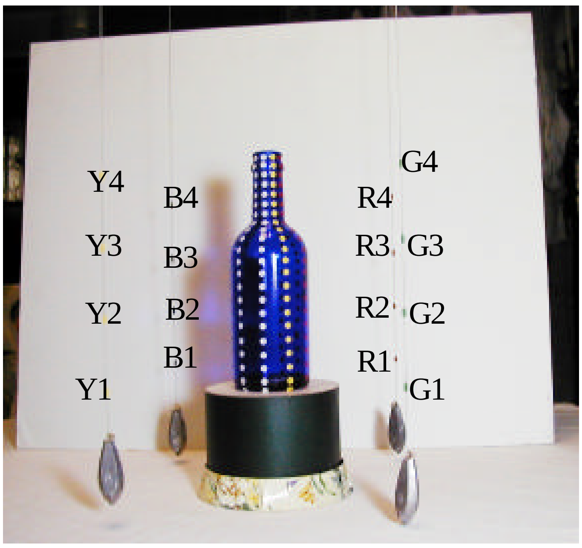

Fig.8 Arrangement of Control Points

Table 9 Coordinates of Control Points

Nos. of Control Points	Three-Dimensional Coordinates (cm)		
	X	Y	Z
R1 (red bottom)	0	0	0
R2 (red 2nd from bottom)	0	5	0
R3 (red 3rd from bottom)	0	10	0
R4 (red 4th from bottom)	0	15	0
G1 (green bottom)	22.8	0.2	0
G2 (green 2nd from bottom)	22.8	5.2	0
G3 (green 3rd from bottom)	22.8	10.1	0
G4 (green 4th from bottom)	22.8	15.1	0
W1 (white bottom)	11.6	-2.1	-10.6
W 2 (white 2nd from bottom)	11.6	2.9	-10.6
W 3 (white 3rd from bottom)	11.6	7.9	-10.6
W 4 (white 4th from bottom)	11.6	12.9	-10.6
Y1 (yellow bottom)	11.6	-2	12.3

6.2.3 Acquisition of Subject's Shape

The shape of the subject was acquired as follows.

(1) The photogrammetric system with GA search was applied to the measuring pass points in each circumferential quarter section of the bottle surface to obtain three-dimensional coordinate data on them.
(2) The three-dimensional coordinate data on the measuring pass points in each circumferential quarter section were corrected by using data on the measuring pass points in the right and left quarter sections appearing in the same photograph.
(3) The shape of the bottom was acquired from the three-dimensional coordinate data on the measuring pass points on the whole surface of the bottom.

6.2.4 Discussion

As shown in Fig.9, the coordinates of the measuring pass points were visualized. Thus, the rough shape of the subject could be acquired successfully.

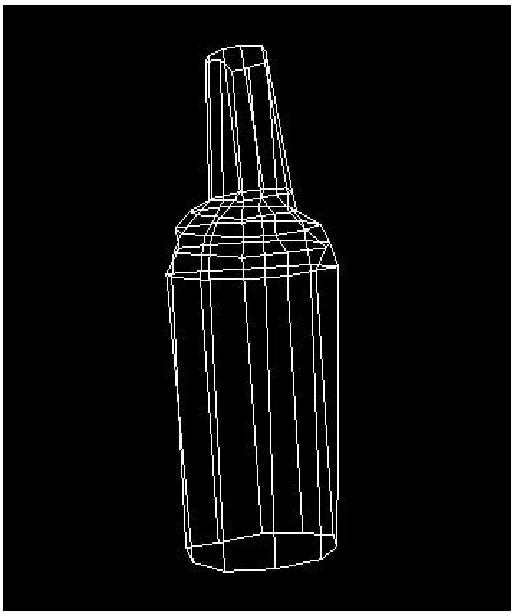

Fig.9 Wire-Frame Model of Subject

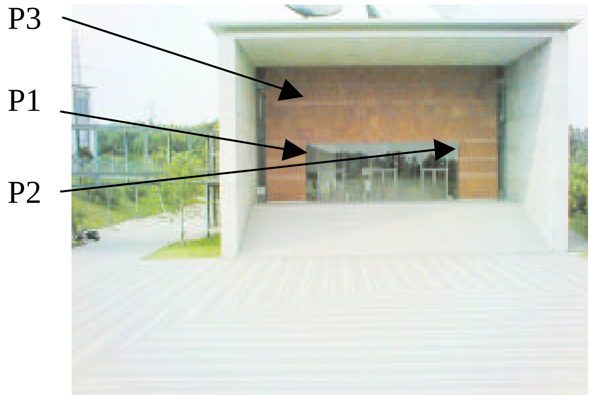

Fig.10 Subject

Table 10 Coordinates of Control Points

Nos. of Control Points	Three-Dimensional Coordinates(m)		
	X	Y	Z
P1	0.00	0.00	0.00
P2	10.67	0.00	0.00
P3	0.00	0.00	4.34

6.3 Application to CG Modeling

In this experiment, the three-dimensional shape data were calculated from the photographs of a subject and CG modeling data were prepared from the shape data. The subject was the graduate school's building in the Takatsuki Campus of Kansai University.

6.3.1 Photographing Method

Because the subject had a complicated shape, the area around the landing of the stairway of the building could not be visualized by photographing from the ground. Accordingly scaffolding was put up 32 m before the building and photographs of the whole building were taken with cameras set 4 m above the ground. Fig.10 shows a photograph of the building thus taken and Table 10 shows the coordinates of the control points.

6.3.2 CG Modeling

By using the three-dimensional coordinate data on the building obtained with the all-solution search system, modeling of the building was performed with the VRML as shown in Fig.11.

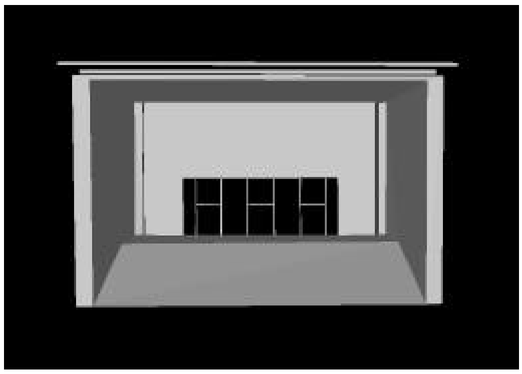

Fig.11 Modeling with VRML

In the modeling shown in Fig.11, since three-dimensional coordinate data were used without preprocessing them, the straight roof and the straight columns were slightly distorted. To correct this shortcoming, the coordinates were averaged. Fig.12 shows the CG model of the building after the correction. Textures were attached on the floor and walls.

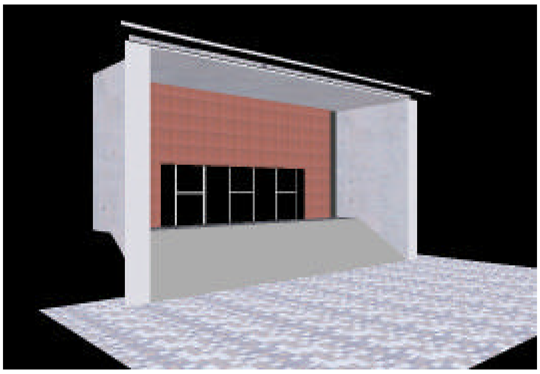

Fig.12 Acquisition of Subject's Shape

7. Conclusions

This study demonstrated that anybody could obtain three-dimensional coordinate data on subjects easily, regardless of kinds of digital cameras and photographing methods, with the system constructed in this study which determined optimal pass points automatically. Established with respect to subjects such as balls and curved surfaces which require a long calculation time was a method for calculating sub-optimal solutions quickly by using genetic algorithm. Because the processing to acquire the corresponding points on the image was made manually, it took a long time to extract the corresponding points. Accordingly the system was unable to make 3D models quickly. The authors will study for automatic acquisition of corresponding points on images and a practical method of easy, quick, accurate 3D modeling.

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