Investigating the accuracy of 3D models created using SfM

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Abstract

Technological innovations in photogrammetry have progressed over time, and civil engineers in Japan have employed this technology for earthworks. Photogrammetry has also been introduced to building construction work, and in particular, it is used in the surveying of buildings and the production of architectural drawings in repair work.

With this motivation, the authors evaluate the accuracy of Three-dimensional (3D) model extraction using structure from motion (SfM) photogrammetry. In particular, the authors evaluate the accuracy of the height measurements (Z axis).

The authors survey the accuracy of a 3D model using a cube with a side length of 5 cm. Our surveying procedure consists of the following four steps:

1. **Place the cube on a turntable, rotate the turntable in 5° increment, and capture 72 photographs.**
2. **Select 12 photographs considering six control points. Edit the control points given their 3D positions in each of the 12 photographs.**
3. **Extract the 3D model using SfM software.**
4. **Import the 3D model and measure the height of the cube at 121 points.**

In this paper, we discuss the differences in the measurement accuracy resulting from the differences in the camera position.

Keywords –

Photogrammetry; SfM; Accuracy; Height

1 Introduction

Technological innovations in photogrammetry have progressed over time, and structure from motion (SfM) is a rapidly advancing method for extracting Three-dimensional (3D) models from multiple overlapping photographs. The Ministry of Land, Infrastructure, Transport and Tourism recommends the introduction of ICT technology to civil engineering work, which is referred to as "i-Construction." As a result, civil engineers have employed this technology in surveying tasks such as earthworks management of the amount of soil in drilling and filling work.

Photogrammetry has also been introduced to building construction work, and in particular, it is used in the surveying of buildings and the production of architectural drawings in repair work. However, it is important to evaluate the accuracy of the three-dimensional positions during the 3D modeling of buildings. Therefore, we evaluate the accuracy of 3D model extraction using SfM photogrammetry. Several researchers have investigated the accuracy of 3D models created using SfM photogrammetry [1] [2]. Several researchers also have investigated the accuracy of Unmanned Aerial Vehicle (UAV) photogrammetry [3]. Terrestrial laser scanning (TLS) is also important technology of 3D modelling. According to D. Skarlatos et al. [4], Bundler-PMVS seems to have an advantage in terms of methodology and accuracy in small and medium size objects and distances. On the other hands, TLS is better in terms of quality and processing time in large scale objects. Here, we evaluate the accuracy of the height measurements (Z axis).

In order to extract a 3D model using SfM, photographs of a building exterior are often captured using a drone. The typical procedure of UAV photogrammetry consists of the following steps (see Figure.1):

1. Measure the control points using a total station. The control points are used to extract the 3D model using SfM.
2. Capture photographs of the entire building exterior using a UAV.
3. Produce a 3D surface model from multiple overlapping photographs using SfM software.
4. Draw a 3D solid model or BIM model from the 3D surface model.

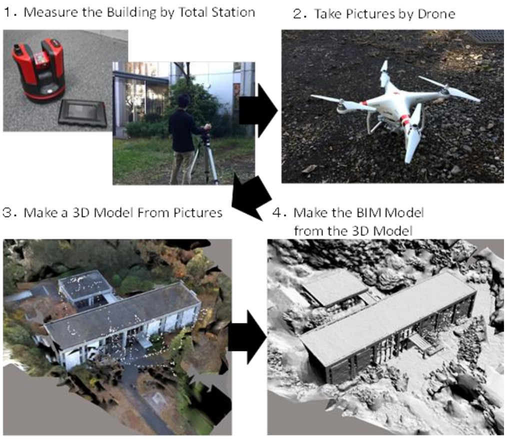

Figure.1 Typical procedure of UAV photogrammetry

In order to create a 3D model with a high accuracy and precision, it is necessary to survey the appropriate flight altitude and turning radius.

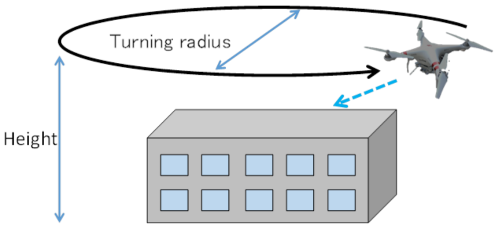

Figure.2 Flight altitude and turning radius

2 Evaluation of the accuracy of 3D model extraction

We evaluate the accuracy of 3D model extraction using SfM photogrammetry. We survey the accuracy of a 3D model using a cube with a side length of 5 cm. We evaluate the differences in the measurement accuracy resulting from the differences in the camera angle and the distance between the subject and the camera.

2.1 Surveying procedure for 3D model accuracy

The distance between the subject and the camera influences the accuracy. In order to investigate this influence, it is necessary to develop a method for capturing the entire exterior of a subject at the same distance and angle. For this, we used a cube with a side length of 5 cm and a turntable. We rotated the turntable in 5° increments and captured 72 photographs.

Our surveying procedure consists of the following four steps:

1. Place the cube on the turntable, rotate the turntable in 5° increments, and capture 72 photographs.
2. Select 12 photographs considering six control points. Edit the control points given their 3D positions in the 12 photographs.
3. Extract the 3D model using SfM software.
4. Import the 3D model and measure the height of the cube at 121 points.

2.2 Photographs of the cube acquired from multiple directions

We acquired photographs to evaluate a 3D model created using photogrammetry. As the subject of the photographs, we created a cube with a known side length of 5 cm. Our camera specifications are listed in Table.1. Figure.3 shows the setup of the camera in front of the cube on a turntable used in this experiment.

Table.1 Camera Specifications

Type	
Camera Name	Nikon 1 J1
Sensor Size	13.2 mm × 8.8 mm
Focal Length	10 mm
Image size	3,872 × 2,592

Figure.3 Camera setup in front of a cube on a turntable

We rotated the turntable in 5° increments and captured 72 photographs. Figure.4 shows the positions of the camera and cube used in the experiment. We acquired 24 sets of photographs captured at various camera heights and distances. An example of some photographs is shown in Figure.5.

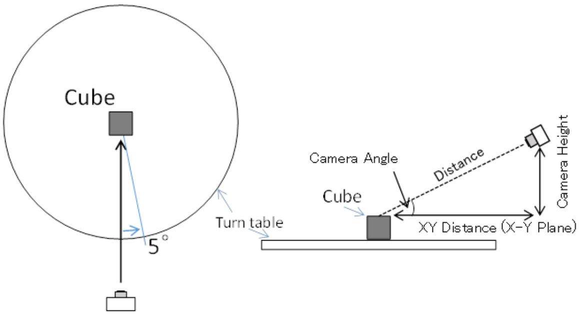

Figure.4 Positions of the camera and cube used in this experiment

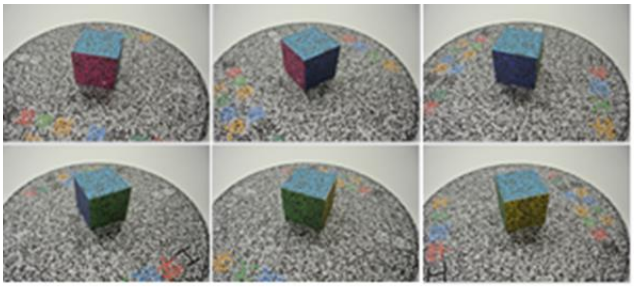

Figure.5 Photographs of the cube from multiple directions

2.3 Selection of control points and checking automatic tie points

SfM software can automatically generate a large number of tie points. However, in order to determine the actual size, we need to define the physical point at which a 3D position is prescribed in the real world. This physical point in the photographs is called the "control point." We determined the control points in different photographs, which correspond to the projections of the same physical point in the scene.

In order to determine the size of the 3D model, we decided to use six control points, as shown in Figure.6. We edited these six control points given their three-dimensional positions in each of the 12 photographs, which consist of three photographs each for four directions. Figure.7 shows an example of the 3D model extracted using SfM software. The blue and red points indicate the camera positions for the 72 photographs, where the red points represent the camera positions of the twelve selected photographs given the six control points.

Figure.8 shows the automatic tie points. We confirmed that a sufficient number of tie points were automatically extracted.

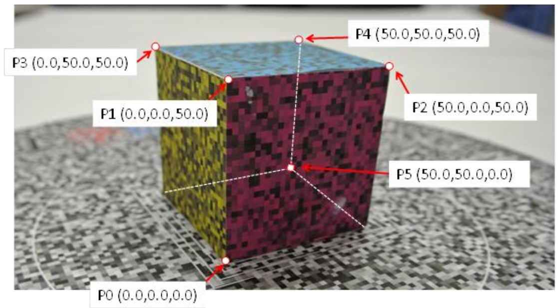

Figure.6 Six control points in this experiment

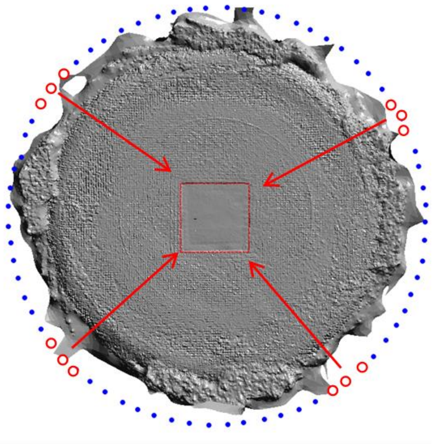

Figure.7 Camera positions for the twelve photographs selected given the six control points

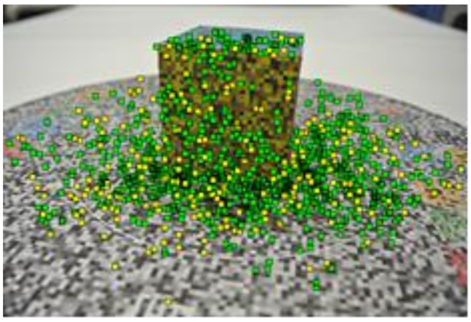

Figure.8 Automatic tie points

2.4 Extraction of the 3D model using SfM software

We then used SfM software to extract the 3D model from the photographs. We used "ContextCapture" to create the 3D models. An example of a 3D model created from the photographs is shown in Figure.9. Figure.10 presents a comparison of the 3D model with a photograph.

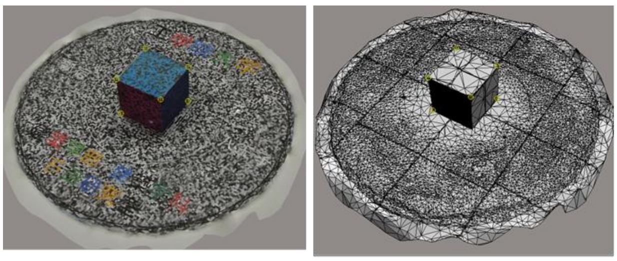

Figure.9 Example of a 3D model created from the photographs

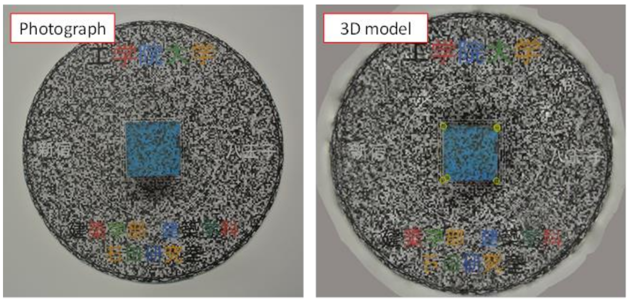

Figure.10 Comparison of the 3D model and the photograph

2.5 Importing a 3D surface model to 3D-CAD

The 3D model was output as STL data and then imported into 3D-CAD. In addition, the camera positions were output as XYZ data and imported into 3D-CAD. Figure.11 shows the 3D model and camera positions in 3D-CAD. The blue points represent the camera positions for the 72 photographs.

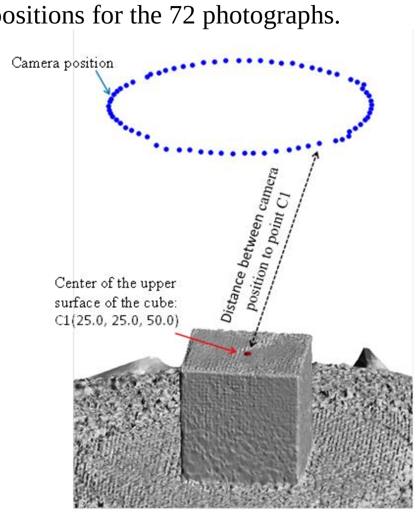

Figure.11 3D model and camera positions in 3D-CAD

We then sliced the cube shown in Figure.11 in the X–Z plane and measured its dimensions. The results are shown in Figure.12. We calculated the distance from each camera position to the center of the top face of the cube (point C1). The coordinates of the point C1 are (25.0, 25.0, 50.0). Figure.13 shows the set of camera positions for the 72 photographs.

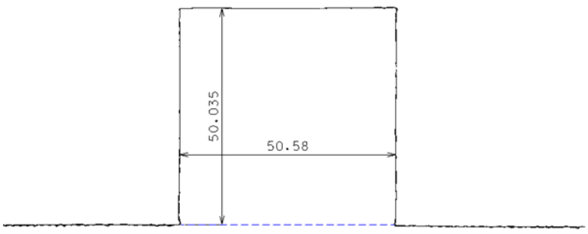

Figure.12 Cube dimensions in the X–Z plane

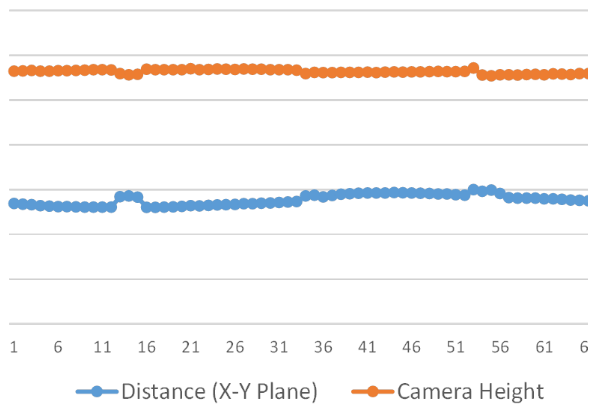

Figure.13 Camera positions for the 72 photographs

2.6 Measurement of the height of the cube

As shown in Figure.14, the 3D model extracted by SfM consists of polygon models. Moreover, the surfaces of the 3D models are not smooth and contain minute irregularities. These minute irregularities lead to variabilities in the cube dimensions. Therefore, in order to eliminate these variabilities in cube dimensions, we decided to measure many points on the cube surface.

Figure.15 shows the measurement positions of the height and width dimensions. The method for calculating the point at which the reference line and surface model intersect consists of the following steps:

1. Select all of the polygons that make up a cube.
2. Remove one polygon and calculate the equation of the plane using three points defining that polygon. (The equation defining a plane is “ax + by + cz + d = 0.” We calculated the variables a, b, c, and d.)
3. Compute an intersection point. Substitute the values X and Y into the equation of the plane “ax + by + cz + d = 0” and then obtain the value for Z.
4. Calculate whether the intersection point is inside the polygon.
5. Repeat Steps 2–4 until all polygons are checked.

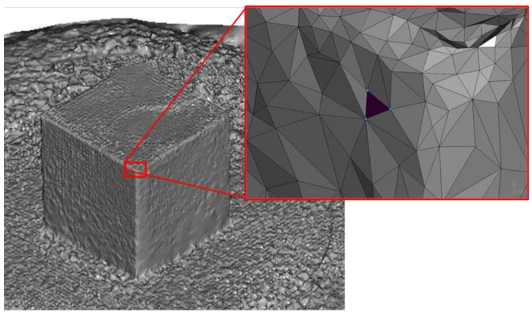

Figure.14 3D model consisting of polygon models

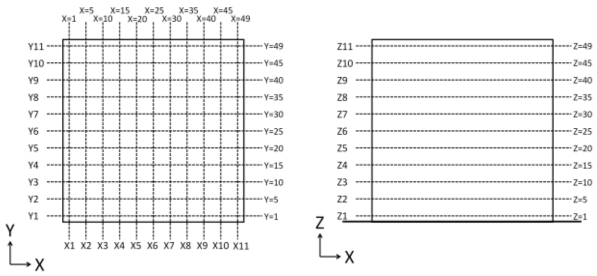

Figure.15 Measurement positions of the height and width dimensions

Figure.16 shows the calculated results for the points at which the reference line and surface model intersect. Table.2 presents an example of the results of the calculation. These 121 points represent the calculation results for the intersection points on the top face of the cube. The camera height for this data is 104.9 mm, the camera angle is 33.8°, and the distance between the camera and the center of the top face of the cube is 188.4 mm. The average value of the height dimension is 50.029 mm, and the sample standard deviation is 0.109 mm.

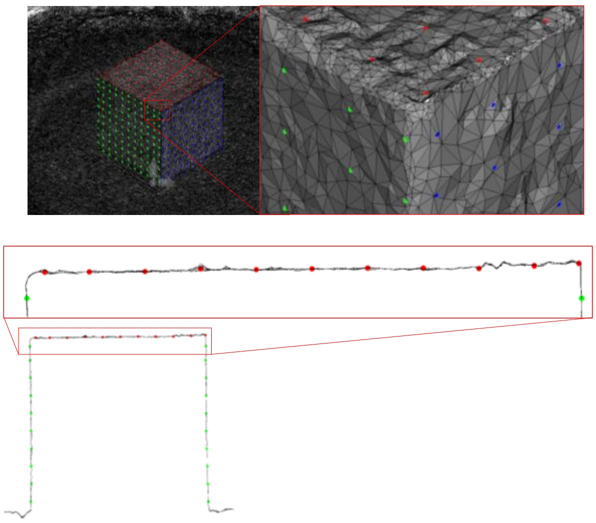

Figure.16 Calculated results for the points at which the reference line and surface model intersect

Table.2 Calculation results for the intersection points on the top face of the cube.

	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10	Y11
X1	49.830	49.986	49.948	49.925	49.931	50.162	50.353	50.113	49.957	50.053	50.037
X2	49.847	50.059	50.109	50.135	50.101	50.130	50.124	50.102	50.131	50.129	50.126
X3	49.824	50.038	49.959	49.922	49.887	49.897	49.887	49.944	50.018	50.172	50.072
X4	49.901	50.070	49.956	49.899	49.862	49.843	49.861	49.880	49.926	50.128	50.099
X5	49.953	50.107	49.989	49.932	49.918	49.947	49.944	49.964	50.035	50.137	50.074
X6	49.973	50.124	49.979	49.913	49.886	49.906	49.929	49.991	49.963	50.083	50.026
X7	49.982	50.146	50.019	49.926	49.912	49.915	49.917	49.909	49.927	50.023	50.064
X8	49.995	50.177	50.108	49.984	49.953	49.912	49.944	49.931	50.080	50.085	50.103
X9	50.083	50.227	50.118	50.041	49.964	49.950	49.924	50.019	50.028	50.063	50.062
X10	50.199	50.235	50.182	50.132	50.085	50.144	50.109	50.042	50.064	50.078	50.137
X11	50.303	50.248	50.239	50.191	50.150	50.087	50.050	50.021	50.019	50.038	50.180

3 Discussion of measurement accuracy

We extracted 3D models from 26 data sets, each of which consisted of 72 photographs, and then measured the height of each 3D model. The measurement results for the height dimension and standard deviation are presented in Table.3.

Figure.17 shows the accuracy of the polygon model for cube No. 3 and No. 11. The red color indicates a part that is larger than its original size. On the other hand, the blue color indicates a part that is smaller than its original size.

As shown in Figure.18, the 3D models for data sets 24, 25, and 26 consist of cubes without a top face. Therefore, they constitute error data. Table.4 summarizes the ground pixel size for each distance between the camera and the subject.

Table.3 Results for the height dimensions and standard deviation

No.	Dimension		Camera position			
	Height dimension (mm)	Sample standard deviation	XY Distance (mm)	Camera height (mm)	Camera angle (°)	Distance (mm)
1	49.98	0.15	417.2	21.1	2.9	417.7
2	50.11	0.28	224.0	16.5	4.2	224.6
3	50.01	0.13	356.5	35.9	5.7	358.3
4	49.84	0.29	242.9	24.5	5.8	244.1
5	50.01	0.17	203.8	30.4	8.5	206.1
6	50.03	0.12	147.6	22.0	8.5	149.3
7	50.07	0.11	349.4	76.1	12.3	357.6
8	50.13	0.12	347.2	129.6	20.5	370.6
9	50.00	0.13	159.7	64.5	22.0	172.3
10	50.37	0.11	377.7	243.4	32.8	449.3
11	50.03	0.11	156.5	104.9	33.8	188.4
12	50.03	0.13	357.5	292.9	39.3	462.1
13	50.14	0.10	700.3	628.6	41.9	941.1
14	50.28	0.10	153.5	152.8	44.9	216.5
15	50.24	0.10	373.6	397.4	46.8	545.4
16	50.50	0.15	186.2	202.1	47.3	274.8
17	50.09	0.19	608.7	806.4	53.0	1010.3
18	50.81	0.40	59.0	87.2	55.9	105.3
19	50.34	0.10	182.7	291.7	57.9	344.2
20	51.57	0.15	71.9	137.2	62.3	154.9
21	51.47	0.40	55.4	112.7	63.8	125.5
22	51.22	0.18	85.0	183.2	65.1	202.0
23	49.70	0.30	189.8	561.5	71.3	592.7
24	Error		189.4	−22.6	−6.8	190.7
25	Error		182.0	−8.2	−2.6	182.1
26	Error		246.7	16.3	3.8	247.3

Table.4 Ground pixel size in this experiment

Distance between camera and object (mm)	200	300	400	500	600	700	800	900	1000
Ground pixel size (mm/pixel)	0.06	0.10	0.13	0.17	0.20	0.24	0.27	0.30	0.34

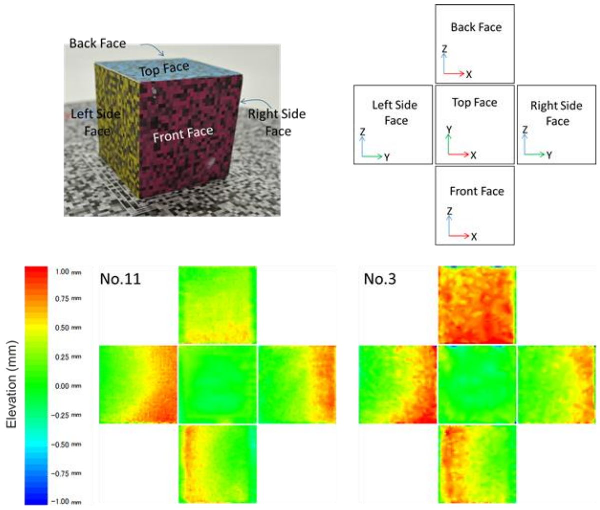

Figure.17 Accuracy of the measurement data for cube No. 3 and No. 11

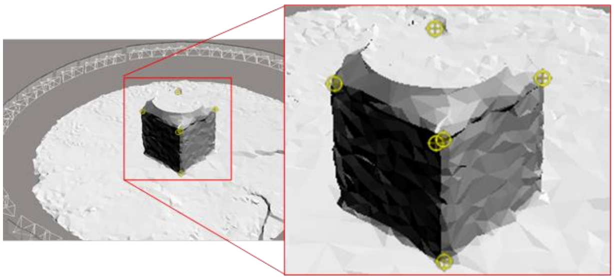

Figure.18 3D model (No. 25) without a top face.

The scatterplot in Figure.19 shows the relationship between the camera angle and the measurement accuracy. The error bars in the scatterplot indicate the sample standard deviation of the height dimension. This scatterplot shows that as the camera angle approaches 90°, the measurement accuracy deteriorates.

The scatterplot in Figure.20 shows the relationship between the measurement accuracy and the distance between the camera position and the center of the top face of the cube.

The camera angle has a stronger influence on the accuracy than the distance to the subject.

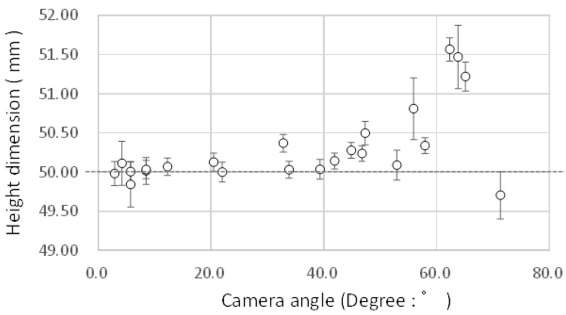

Figure.19 Relationship between the camera angle and the measurement accuracy

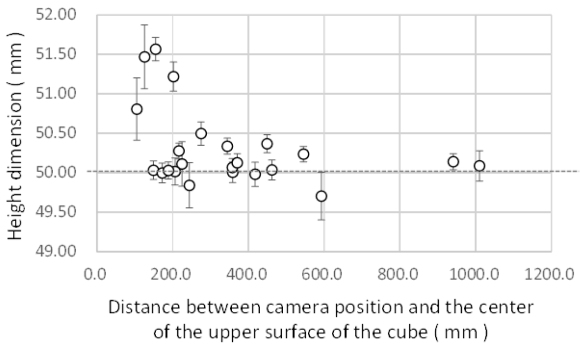

Figure.20 Relationship between the camera distance and the measurement accuracy

4 Conclusion

In this study, we have evaluated the height measurement accuracy of 3D model extraction using SfM photogrammetry. We have surveyed the accuracy of a 3D model using a cube with a side length of 5 cm. We extracted 3D models from 26 data sets, each of which consisted of 72 photographs, and then measured the height of each 3D model. As a result, we have determined that the accuracy of the height dimension is influenced by the camera angle.

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