Research article

Verifying Optimum Flying Conditions for UAV Photogrammetry in Assessing Hydro-structural Facilities

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Received 9 February 2023 Accepted 25 May 2023 (*Corresponding Author)

Abstract Monitoring hydro-structural infrastructure is becoming an important and challenging issue. In Japan, there are an increasing number of aging hydro-structural facilities, which need to be inspected to guarantee their strength and durability function. Unmanned Aerial Vehicle (UAV) photogrammetric images have been used in the detection of structural deterioration of various infrastructure. However, there is a challenge in determining the optimum flying conditions (altitude, angle of camera, and flying patterns) of UAVs for obtaining images. The designs, shapes, and sizes of hydro-structural facilities also pose a challenge for obtaining ideal images. In this study, verification of various flying conditions for producing images and 3D models was proposed for water gates and open surface water channels. Additionally, an evaluation method for the images and 3D models was suggested. In this study, UAV was used for visual inspection and obtaining the image of the water gate and open surface water channel at the Tone diversion gate in Saitama, Japan. Various geometric patterns were pasted on the surface and walls of the structures to evaluate the detection of the patterns with the images taken from UAVs at different flying conditions. The obtained ortho-mosaic images were processed by a PIX4D mapper to obtain a point cloud-based 3D model and were compared with the actual measurements of the patterns. The results of the study suggested that altitude and camera angles affected the quality of images significantly. Cameras at lower angles provided better images, although cameras at high altitudes with wider angles also demonstrated a high degree of efficiency. The circular flying pattern generated satisfactory results, where flyovers were conducted multiple times while changing altitudes and angles of the camera. Additionally, this study proposes a method named "leveling" for the evaluation of images and 3D models.

Keywords UAV photogrammetry, hydro-structural assessment, 3D models, level

INTRODUCTION

In Japan, many hydro-structural facilities were constructed during the post-war period and are now in deteriorating conditions (MAFF, 2022). The Ministry of Agriculture, Forestry and Fisheries has begun full-scale efforts for 'stock management' to extend the service life of facilities and reduce life cycle costs to reduce such damage and ensure safe living conditions in the future. Stock management consists of continuous facility monitoring, periodic functional diagnosis, deterioration forecasting based on this, investigation of efficient deterioration countermeasure methods, formulation of functional maintenance plans, and implementation of appropriate countermeasure works promptly. Among these, facility monitoring, and functional diagnosis are often time-consuming and labor-intensive, such as visual inspection, percussion inspection, and surveying. However, the workforce and inspection technicians are decreasing due to a decrease in population and aging, resulting in a serious shortage of manpower, (Tabata et al., 2018). Machines and robots are expected to play an active role in solving these problems. Unmanned Aerial Vehicles (UAVs) can take aerial photographs by flying at lower altitudes than manned aircraft and other vehicles that have been commonly used with high-resolution aerial photographs (Miyazaki et al. 2018). Therefore, research is being conducted to construct 3D models and use them for inspections with the aim of recording information on deterioration and damage at a higher resolution from the aerial photographs taken (Saito et al., 2022). Previous studies have shown that a 3D model can be produced in detail from aerial images by flying a UAV at low altitude and taking photographs, however, the sides of a building cannot be accurately modeled when the camera angle is directly below the angle of a building (Miyazaki et al., 2018). It has also been found that cracks and exposed rebar can be identified from images taken by UAVs (Tabata et al., 2018). However, there lacks of optimal imaging technique for hydro-structural facilities by varying the imaging conditions, such as flight altitude and camera angle.

OBJECTIVE

The objectives of this study were to verify optimum flying patterns for UAV imaging and 3D modeling focusing on camera altitude and angles in hydro-structural facilities assessment. Additionally, this study tries to develop a method for quantitatively evaluating 3D models.

METHODOLOGY

Description of the Study Site

In this study, a field survey was conducted in two hydro-structural facilities of Tone Water Supply Works of Japan Water Agency in Gyoda City, Saitama Prefecture, Japan. The water gate and open surface water channel were the target structures for this study (Fig.1). The width and height of the water gate were approximately 17.4 m and 7.3 m respectively. Likewise, the width and height of the channel were 14.4 m, and 2.5 m, respectively.

Fig. 1 Water gate (left) and open surface water channel (right)

Installation of Ground Control Points (GCPs) and Real Time Kinetic Survey

Ground control points (GCPs) were set up around the facility and their positional information was measured. The GCPs were surveyed using the RTK satellite positioning system (Real Time Kinematic Global Navigation Satellite System). The RTK survey was done to increase the location accuracy.

Flight Conditions of UAV Survey

Small rotary-wing UAVs (Inspire 2/DJI and ANAFI/Parrot) were used for aerial photography, with the Zenmuse X5S (RGB) camera mounted on the Inspire 2 and RGB camera on ANAFI (Fig. 2). Inspire 2/DJI was used for the water gate, and ANAFI/ Parrot was used for the water channel due to its easy operation for a smaller area. Aerial photography was performed using a flight planning application (Pix4D capture/Pix4D, Pix4D scan/Pix4D) installed in UAVs. The UAV was flown in double grid and circular flight for the water gate and grid (oblique and horizontal) for the water channel with an overlap of 80% for both the top and side. The flight altitude was set to the lowest altitude at which it was possible to fly, with the grid/double-grid flight pattern flown at 20 m, and the circular flight pattern at 20 m, 30 m, and 40 m (Table 1). The camera angle was 45°, 60° and 80° for all flight paths (Table 2).

Table 1 Flight plan parameters for the Water gate survey

Flight path	Flight altitude (m)	Flight angle (°)
Double grid	20	45, 60, 80
	20	45, 60, 80
Circular flight	30	45, 60, 80
	40	45, 60, 80

Table 2 Flight plan parameters for open water channel survey

Flight path	Flight altitude (m)	Flight angle (°)
Oblique grid	20	60
Horizontal grid	20	45, 60, 80

Fig. 2 Drones used in this study
Inspire 2 (left) and ANAFI (right)

Dimensional Measurements of the Hydro-structural Facilities

Measurements of facilities were conducted for the target structures. Seven measurements were taken for sections of the water gate and two measurements were carried for the channels, respectively. A measuring tape was used for the measurements, and measurements were taken while pulling the tape at each end to prevent the center from sagging.

Conversion of Aerial Image Data into 3D Models

Pix4D mapper (Pix4D) application was used to create 3D models (point clouds) from aerial images (USDA, 2022). First, aerial images were added to the Pix4D mapper software for initial processing. In the initial processing, characteristics of geographical features were extracted as key points from the images added to the Pix4D mapper. Images with the same key points are then searched for and matched. The camera's internal and external parameters were corrected. To improve the positional accuracy of the 3D model and the ortho mosaic image, GCP latitude, longitude, and elevation data were added and optimized for re-estimation with respect to camera positioning information and image distortion. Finally, point clouds were densified based on automatic tie points and compared and evaluated from the resulting 3D models.

Evaluation of the Model

Reproducibility of 3d Models with the Actual Image

The reproducibility of the target structures in the 3D models (point clouds) created from different flying conditions was checked. The point cloud data were compared with the aerial images to assess the differences. The dimensions of the 3D model were measured by creating polylines in Pix4D mapper. The polylines were created in such a way that they were close to the positions measured during the survey; three polylines were created at one measurement site, the mean error and standard deviation from the actual measurement were calculated, and the values were compared for each flying condition.

Leveling of 3d Models and Actual Images

An evaluation method unique to this study was developed where three types of patterns (triangle, circle, and square) were classified into levels from 1 to 5 (Fig. 3). The points and levels were set so that the smaller the side length of the pattern (shown in fig. 3 by yellow line) higher the point and level. For the triangular pattern, point 1 was given for level 1 where the side length was 20 cm, likewise, points and levels were assigned for each length and pattern. Additionally, the level was set to 0 if the figure was not visible in the 3D data. These patterns were pasted on the surface of the target structures and aerial images were taken. Verification for actual images and 3D models was performed with points allotted for each level. The aerial imaging conditions were evaluated by comparing the average of the points. Furthermore, multiple regression analysis was performed to assess the influence of altitude and camera angle on the levels.

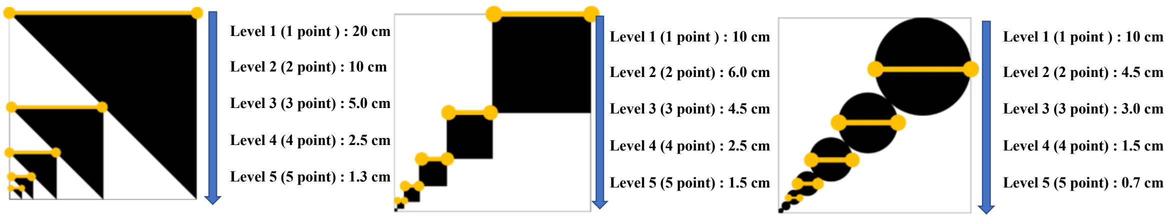

Fig. 3 Geometric patterns with dimensions and allocated points for the level

RESULTS AND DISCUSSION

Reproducibility Evaluation of 3D Models (Point Clouds)

A 3D model was created by combining aerial images obtained under various flight conditions to verify the differences and the dimensional error compared to the measured facility. The results showed that for the double grid flight pattern, the camera angle affected the results (Fig. 3, left image). The reproducibility was high for 45° followed by 60° angles for the pillar sections of the gate. Similar results were obtained for circular flight patterns, where reproducibility was high for 45° followed by 60° angles (Fig. 4, right image). On the other hand, when the camera angle was at an angle of 80°, the reproducibility increased with altitude for the upper part of the water gate indicating that modeling depended on the flight altitude (Fig. 5, left image). Furthermore, there was no difference in recognizing the pattern pasted insides of the open channel for all flight conditions, however, at a camera angle of 80°, reproducibility was lower (Fig. 5, right image). In addition, a comparison of the dimensions of the facility measured and the dimensions of the 3D model showed that the errors were within 10 cm for all flight methods (Table 3, Table 4, Table 5 and Table 6).

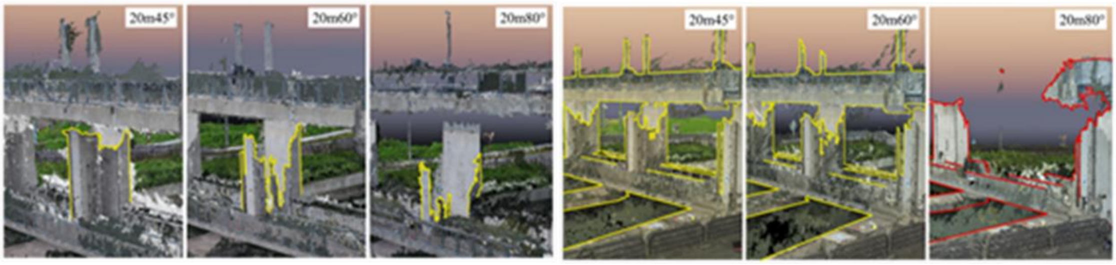

Fig. 4 3D point cloud model created from aerial images of water gate
Grid flight pattern (left) and circular flight pattern (right) at varying camera angles at an altitude of 20 m

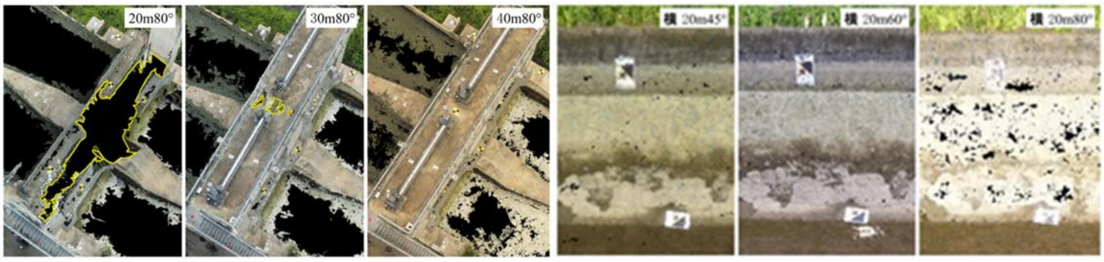

Fig. 5 3D point cloud model created from aerial images of a circular flight pattern over a flow control
Weir at different altitudes at a camera angle of 80 ° (left image), 3D points cloud model created from aerial images of a grid flight over an open channel at an altitude of 20 m with varying camera angles (right image)

Evaluation of Level

The result of the level is shown in Tables 3 to 6. In the case of the double grid flying pattern, when the UAV flying altitude was fixed and the camera angle varied, the level became lower as the camera angle was moved closer to the nadir, indicating that the camera angle had a significant effect on leveling. In addition, it was understood that too many photographs are not good for the leveling, since the level of the result of the analysis of the three patterns together was not the highest. In circular flight, the higher the flight altitude, the lower the level, indicating that the altitude of the flight also has a significant effect.

Table 3 Level and dimensional error assessment during double grid flight over water gate

Altitude (m)	Angle (°)	No. of pics	Level evaluation		Measurement error (cm)	
			Aerial image	3D model	Avg. error	Std. deviation
20	45	440	3.12	1.28	2.41	±3.51
20	60	314	2.81	1.20	1.67	±2.57
20	80	747	2.79	0.93	1.77	±2.38
Total		1501	2.97	0.84	1.35	±1.85

Furthermore, from the result of levels at each altitude when the camera angle was 80 °, it was found that it was necessary to take photographs while keeping the camera angle close to the nadir. The results of the multiple regression analysis of altitude and angle effect on the image and model levels for the double grid and circular flight are shown in Tables 7 and 8. According to the analysis, the influence of altitude is high at both the image levels and model levels. Furthermore, at the model level, the angle was also found to influence the level, although not to a large scale.

Table 4 Level and dimensional error assessment of circular flights over water gate

Altitude (m)	Angle (°)	No. of pics	Level evaluation		Measurement error (cm)	
			Aerial image	3D model	Avg. error	Std. deviation
20	45	75	2.65	0.90	2.05	±3.01
20	60	78	2.60	0.98	1.82	±2.24
20	80	80	1.66	0.56	1.60	±3.63
30	45	78	1.88	0.90	3.51	±4.71
30	60	81	1.99	0.79	2.48	±3.69
30	80	80	1.87	0.67	2.22	±3.14
40	45	76	1.39	0.68	2.77	±3.54
40	60	78	1.36	0.67	3.50	±4.53
40	80	78	1.28	0.74	1.98	±2.77

Table 5 Level and dimensional error assessment for each combined circularly flown aerial image of water gate

Combination flight pattern		No. of pics	Level evaluation		Measurement error (cm)	
Circular flight	Circular flight		Aerial image	3D Model	Avg. error	Std. deviation
20 m 45°	30 m 60°	156	2.70	1.28	1.94	±2.59
20 m 45°	30 m 80°	155	2.77	1.30	1.44	±2.18
20 m 45°	40 m 60°	153	2.83	1.24	1.73	±2.25
20 m 45°	40 m 80°	153	2.77	1.18	1.20	±2.07
20 m 60°	30 m 80°	158	2.79	1.26	1.63	±2.21
20 m 60°	40 m 80°	156	2.74	1.24	1.65	±2.61
30 m 45°	40 m 60°	156	2.07	0.90	1.37	±1.76
30 m 45°	40 m 80°	156	2.04	0.93	2.44	±2.85
30 m 60°	40 m 80°	159	2.29	0.89	1.53	±1.88
20 m 45° + 30 m 60° + 40 m 80°		234	2.79	1.21	1.87	±2.86
Total		704	2.64	0.98	1.70	±2.10

Table 6 Level and dimensional error assessment during grid flying over an open water channel

Direction	Altitude (m)	Angle (°)	No. of image	Level evaluation		Measurement error (cm)	
				Aerial image	3D model	Avg. error	Std. deviation
Oblique 1	20	60	258	3.08	2.00	2.33	±2.94
Oblique 2	20	60	240	3.03	1.96	3.17	±1.17
Oblique 1and 2	20	60	498	3.05	2.06	2.00	±1.26
Horizontal	20	45	158	2.68	1.23	4.33	±3.50
Horizontal	20	60	330	3.18	1.82	4.83	±5.32
Horizontal	20	80	126	2.37	1.18	3.00	±5.40

Table 7 Multiple regression analysis of level (Images)

	Coefficient	Std. deviation	*t*	p-value
Altitude	-0.0636	0.0115	-5.5186	***
Camera angle	-0.0105	0.0067	-1.5765	

*$p < 0.01$ *** $p < 0.05$ ** $p < 0.1$ **

Table 8 Multiple regression analysis of level (3D model)

	Coefficient	Std. deviation	*t*	p-value
Altitude	-0.0144	0.0059	-2.4277	**
Camera angle	-0.0063	0.0034	-1.8443	*

*$p < 0.01$ *** $p < 0.05$ ** $p < 0.1$ **

CONCLUSION

In this study, the optimum UAV flying conditions for UAV imaging were investigated for water gate and open surface channels. The aerial imaging conditions were compared using three methods: reproducibility of the 3D model, comparison of the measured dimensions of the facility and the dimensions of the 3D model, and an original evaluation method called 'leveling', to investigate the most suitable flight pattern. According to the results of this study, the following conclusions were made: (i) Images obtained by circular flight patterns with various combinations were effective for the water gate. (ii) For open surface water channels, the camera angle should not be close to the nadir. (iii) For quantitively assessing aerial imaging, figure leveling is useful. (iv) For planning UAV imaging assessment of hydro-structural facilities, the altitude of the UAV should be set followed by the angle of the camera. However, the results of this study showed deficiencies in modeling the upper part of the columns and shadowy areas, and the upper part of the columns from aerial images. In the future, it is desirable to analyze images taken from the ground to compensate for areas such as the tops of columns, which are difficult to take images by automatic UAV flight. In addition, as hydro-structural facilities are in different shapes and sizes, it is necessary to conduct more similar studies.

ACKNOWLEDGEMENT

The authors like to acknowledge Tone Water Supply Works of Japan Water Agency for assisting and providing guidance for the survey.

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