Autonomous UAV flight using the Total Station Navigation System in Non-GNSS Environments

A.Ishii[a], T.Yasuno[a], M.Amakata[a], H.Sugawara[a], J.Fujii[a], and K.Ozasa[a]

[a]Yachiyo Engineering Co., Ltd., Research Institute for Infrastructure Paradigm Shift
E-mail: akri-ishii@yachiyo-eng.co.jp, tk-yasuno@yachiyo-eng.co.jp, amakata@yachiyo-eng.co.jp, sugawara@yachiyo-eng.co.jp, jn-fujii@yachiyo-eng.co.jp, kh-ozasa@yachiyo-eng.co.jp,

Abstract –

In this study, we propose autonomous UAV flight using the total station to estimate self-localization at a dam in a non-global navigation satellite system (GNSS) environment and suggest a flight path planning method for the UAV's flight position. As a result of the UAV's stable autonomous flight, a certain distance from the dam body's surface can be maintained by flying accurately along the planned path, allowing for uniform quality and high-resolution images to be captured. Moreover, geotags can be added to the image by measuring the flight position of the captured images; this is achieved via the total station, which can track the UAV even in a non-GNSS environment. Resultantly, the accuracy of the three-dimensional reconstruction model using photogrammetry technology can be improved.

We further implement a field study to demonstrate the utility of the proposed approach. Moreover, we propose aging detection using AI analysis.

Keywords –

Autonomous UAV flight; Non-GNSS; Total station navigation system; Flight path planning; Dam

1 Introduction

An unmanned aerial vehicle (UAV) can fly autonomously via self-localization and flight attitude stabilization technologies, including global navigation satellite systems (GNSSs) and various sensors; e.g., gyroscopes, an accelerometer, a barometric sensor, and inertial measurement unit (IMU). Therefore, UAVs have recently seen increasing use in various inspections [1,2,3,4] owing to their high functionality and practicality. Conversely, autonomous UAV flight in outdoor environments, where GNSSs are unavailable, is a challenge.

In Japan, many social infrastructures are aging and inspections are necessary for maintenance. As shown in Figure 1, it is necessary to efficiently capture the dam body's surface image for an inspection or survey, via a digital camera mounted on the UAV. However, GNSSs cannot normally be used because the radio waves from global positioning system (GPS) satellites do not reach mountainous areas; i.e., a dam's location cannot be determined, or a multipath caused by interference and phase shift of the radio waves occurs around a dam body.

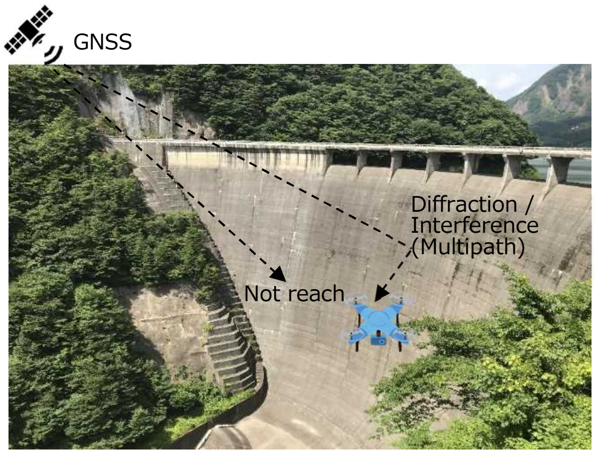

Figure 1. Depiction of the GNSS environment at the dam. The GNSS is likely to be unavailable or unreliable due to sky occlusion in mountainous areas and multipath around the large structures.

Therefore, the UAV needs to be manually controlled by a pilot, which increases the UAV operator workload and makes it difficult to: 1) Obtain high-resolution images with uniform quality for inspection and management, or 2) prevent human errors, such as lapses in capturing the image. Hence, the realization of autonomous UAV flight in a non-GNSS environment is required.

The remainder of this paper is organized as follows. Section 2 introduces the related works. Section 3 presents the proposed system applied to autonomous UAV flight at the dam in a non-GNSS environment. Section 4 validates the proposed system in a field study. Section 5 proposes the flight opportunity. Finally, the conclusions and future work are discussed in Section 6.

2 Related Works

There are three important technologies for obtaining clear and high-resolution images of uniform quality to inspect and manage the dam's body via a digital camera mounted on a UAV: the flight path planning method, self-localization for autonomous UAV navigation, and photogrammetry technology. An overview of each method is presented below, with an application of this research.

2.1 Flight Path Planning Method

A flight path is planned by successively creating way points (WPs) and arranging and connecting them continuously. The WPs contain the latitude, longitude, and altitude of the UAV and action information, such as the change in nose and flight speed direction at that time. There are three approaches for setting WPs: manual creation, simulation-based, and pilot flight trajectory.

2.1.1 Manual Creation Method

This method requires the pilots to manually and sequentially set all the WPs using the general autopilot software function.

However, it is difficult to accurately set the WPs near the reservoir on the upstream side of the dam body or in the complicated shape of the dam body and its surroundings as the terrain information available to pilots and software is only approximate.

2.1.2 Simulation-Based Method

If there is a three-dimensional point cloud data of the dam, it is possible and useful to accurately set the WPs to maintain a certain distance from the dam body surface via coordinate calculation.

However, many dams do not have three-dimensional point cloud data as they are time-consuming and costly. Therefore, an inexpensive, highly accurate flight path planning method for dams that do not have three-dimensional point cloud data is required.

2.1.3 Using Pilot Flight Trajectory Method

Some commercial autopilot software attached to general consumer UAVs, such as DJI, possess a function for recording the flight trajectory of the pilot [5], allowing for flight path planning. In addition, there is a method that collects and analyzes many pilot's flight paths and analytically plans a path from them [6].

There are many artificial errors in the flight trajectory via manual UAV operation as the position of the UAV does not work in a non-GNSS environment. In addition, the GNSS flight trajectory coordinate is noisy and inaccurate. Therefore, this low-precision GNSS flight trajectory coordinate is not suitable for inspecting flight paths. However, it is a useful method if the flight trajectory can be accurately measured, even in a non-GNSS environment.

2.2 Self-localization Technology for UAV Autonomous Navigation

For the UAV to automatically navigate along the flight path, it needs to estimate its flight position. The general basic structure of the UAV is shown in Figure 2. The autonomous navigation of a UAV can be classified according to the difference in the self-localization estimation method shown in Figure 2. An overview of each method is presented below.

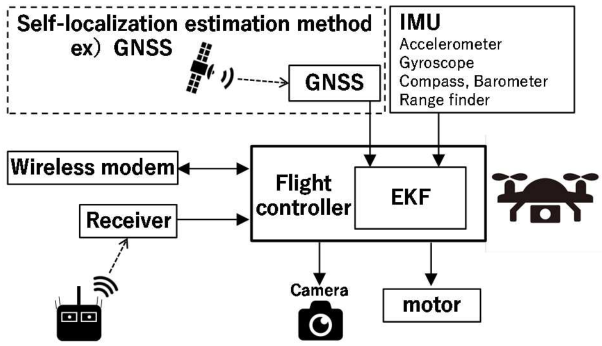

Figure 2. The general basic UAV structure

2.2.1 GNSS Navigation

GNSS positioning information is used as a self-localization estimation method and can be received by a small and inexpensive sensor mounted on the UAV. Therefore, this is the most popular method of autonomous UAV navigation using widespread communication technology.

However, as GNSSs cannot normally be received at a dam, this navigation system cannot be adopted. Even if GNSSs can be received normally, the positioning error is in the order of several meters or more, which is not suitable for inspection flights that require high accuracy.

2.2.2 SLAM Navigation

Simultaneous localization and mapping (SLAM) technology consists of front-end processing that focuses on sensor signal processing and back-end processing that focuses on optimizing the pose graph and performs simultaneous self-localization estimation of a moving body and constructs a three-dimensional spatial map. In addition, SLAM is approximately classified into visual SLAM and light detection and ranging (LiDAR) SLAM, according to the front-end processing. As feature points, visual SLAM uses the color and light/dark information of each pixel of the camera or image sensor image, and LiDAR SLAM uses the point cloud coordinates measured by the laser sensor (distance sensor). In both SLAMs, the three-dimensional spatial map is recognized by matching the feature points, the movement is estimated sequentially, and the self-localization is estimated via accumulation.

Although this is a self-localization technique that does not depend on GNSS, some problems do exist:

- The position estimation errors accumulate and are not cleared; hence, the estimated position does not return to a true value.
- The self-position is lost if the feature point extraction fails.
- A high calculation cost for processing and optimization is required.
- The flight safety and image efficiency are reduced because the UAV flies close to the target object so as not to lose the feature points.

2.2.3 Total Station Navigation (TS Navigation)

The total station is a surveying instrument comprising a light wave rangefinder, which measures distance, and a theodolite, which measures angles. In this method, a prism is attached to the UAV; the prism's position is measured as the flight location via the total station. The UAV recognizes the self-location by feeding back the measurement result to the UAV. Originally, as a method of enabling autonomous flight even in a non-GNSS environment, this technology was predominantly developed for indoor flight using a consumer UAV [7].

We also attempted to apply it to autonomous UAV flight for dam body surface inspection. However, the flight control of the consumer UAV is a black box, and the fail-safe function cannot be completely canceled. Thus, the UAV did not fly autonomously owing to limited flight control and altitude.

It is a useful technique if flight control is possible as the position information accuracy is higher than that of other methods.

2.2.4 Cooperative Navigation

Two UAVs fly at the same time and communicate with each other. The first UAV flies where GNSS can be received normally, and the second UAV flies in a non-GNSS environment. The second UAV receives the position information estimated via the first UAV's optical tracking in real-time and can recognize the self-location by processing this information with low latency [8,9].

Advanced and complicated control technology for two UAVs is also required. Moreover, large-scale structures, such as dams, cannot be shot over the course of one flight as the flight time is limited by the battery. Thus, it is very difficult to maintain two UAVs simultaneously, and several operational issues exist.

2.2.5 Marker Recognition Navigation

The AR markers, or QR codes, placed on the flight route are successively read via the camera mounted on the UAV, and flight control can be enabled via recognition of the respective information on the marker; e.g., flight position, flight direction, travel, and distance.

Thus, this method enables autonomous flight, even in a non-GNSS environment; it is easy to prepare for indoor use, by placing a paper with a marker printed on the wall, but is difficult to install, manage, and maintain for outdoor use in large-scale infrastructure, such as a dam.

2.3 Photogrammetry technology

In recent years, the development of a scale-invariant feature transformation (SIFT) algorithm has automated the extraction and matching of image feature points and camera lens calibration. Therefore, it has become possible to easily reconstruct the three-dimensional model via SfM (structure from motion) and MVS (multi-view stereo).

As GNSSs cannot normally be received at the dam, it is not possible to add geotags to images captured using the digital camera mounted on the UAV. Therefore, three-dimensional reconstruction relies only on the feature points of the image. However, a problem is presented as the shape of the dam is distorted and approximate, even if the three-dimensional reconstruction model is corrected via GCPs (ground control points), as GCPs exist only in a limited flat space, such as the dam's top.

3 Proposed System Overview

This paper proposes a self-localization technique by using the total station applied to an autonomous UAV flight at a dam in a non-GNSS environment. In addition, UAV tracking by the total station is enabled to plan a highly accurate flight path for inspection and to add geotags to images. Therefore, it is possible to properly inspect and manage the entire dam body by analyzing the clear high-resolution images of uniform quality captured using a digital camera mounted on a UAV.

3.1 TS Navigation System Configuration

Figure 3 shows the proposed UAV autonomous navigation system at the dam using the total station. First, the coordinates of the installation position, the direction of the lens, and the vertical angle are set to the total station. Next, a prism is attached to the UAV, allowing flight position measurement by automatically tracking the total station; the measurement result is sent to the UAV. Finally, the flight position is automatically adjusted while the error between the estimated position and the WPs is checked.

The equipment used in this system is shown in Table 1. The image of the prism attached to the UAV is shown in Figure 4.

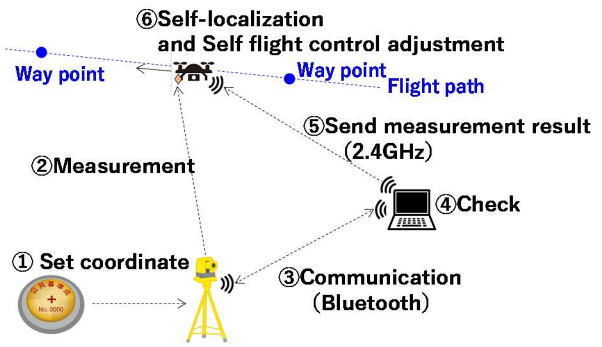

Figure 3. Image of the proposed UAV navigation system using the total station.

Table 1. System specification

UAV	
Product name	QC730 produced by ENROUTE
Size [mm]	D1100×W1100×H310
Flight controller	Pix hawk
Sensor	Accelerometer (3 axes), Gyroscope (3 axes), Compass, Barometer, Light ware LW20
Total Station	
Product name	TOPCON GT-1005
Prism	Leica Geosystems GRZ101
Camera	
Product name	Sony α6300
Lens	SEL35F28Z
Recording pixels	6000×4000

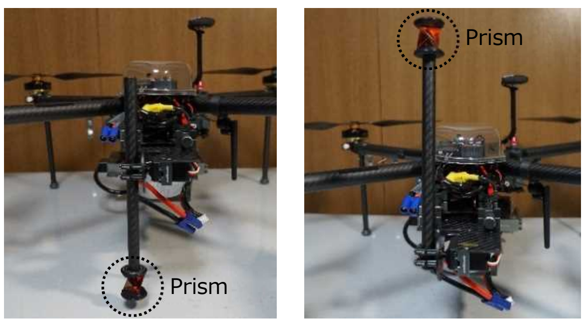

Figure 4. The image of the prism attached to the UAV. The prism is attached to the lower side of the UAV when tracking from below (left) and to the upper side of the UAV when tracking from above (right).

3.2 Flight Path Planning with Pilot Flight Trajectory

It is necessary to plan the flight path to confirm the resolution required by the AI analysis and to accurately set the WPs that are a certain distance away from the dam body surface, considering the performance of the digital camera.

In this study, if three-dimensional point cloud data of the dam exist, the flight path for inspection, which maintains a certain distance from the surface of the dam body, is planned by coordinate calculation. Conversely, if there is no three-dimensional point cloud data of the dam, the flight trajectory of the pilot's manual operation is used to plan an inexpensive, efficient, and highly accurate flight path. The UAV tracked at the total station uses the position information to control its attitude, even by manual operation in a non-GNSS environment, resulting in a stable flight path. This stable flight enables accurate flight path planning by using the self-position estimated by the UAV as the WPs while measuring the distance to the dam body surface with the range finder sensor mounted on the UAV.

3.3 Improved Accuracy of Photogrammetry Technology

In this study, geotags can be added to the image by measuring the flight position at which the image is taken and using the total station, which even tracks the UAV in a non-GNSS environment. Therefore, it is possible to accurately reconstruct a three-dimensional model using the captured image's geotags, as shown in Figure 5.

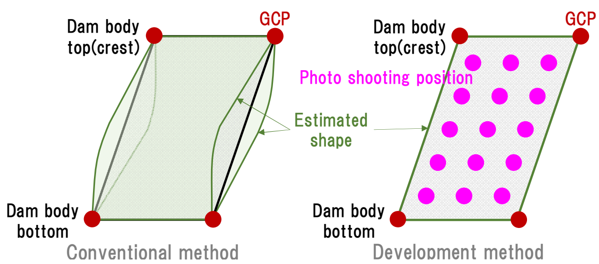

Figure 5. Improving the accuracy of the three-dimensional modeling

4 Field Study

In this paper, we implement a field study to demonstrate the utility of this proposed system for two types of concrete dams in Japan, as shown in Table 2. In a field study, uniform quality and high-resolution images of 2.0 mm/pixel are required for the dam body's inspection by AI analysis.

Table 2. Dam structure specifications

Classification ID	Dam-1	Dam-2
Dam type	Gravity	Arch
Dam height[m]	156.0	94.5
Dam top length[m]	375.0	215.0
Three-dimensional point cloud data	No-exist	Exist

4.1 Flight Path Planning

The flight path has to be planned approximately 18.0 m from the dam body's surface as per the AI analysis request. Since the horizontal flight exerts a lower battery load and involves more flight time than those of vertical flight, the flight path has to be essentially horizontal.

The flight path is planned by the pilot flight trajectory because there is no three-dimensional point cloud data at Dam-1 as shown in Table 2. Figure 6 shows the UAV flying and tracking by the total station at Dam-1. This flying UAV is manually operated while being tracked by the total station. Figure 7 shows an example of the WP results and the planned flight path using the manual flight trajectory of the UAV, via tracking using the total station; thus verifying that an accurate flight path can be created.

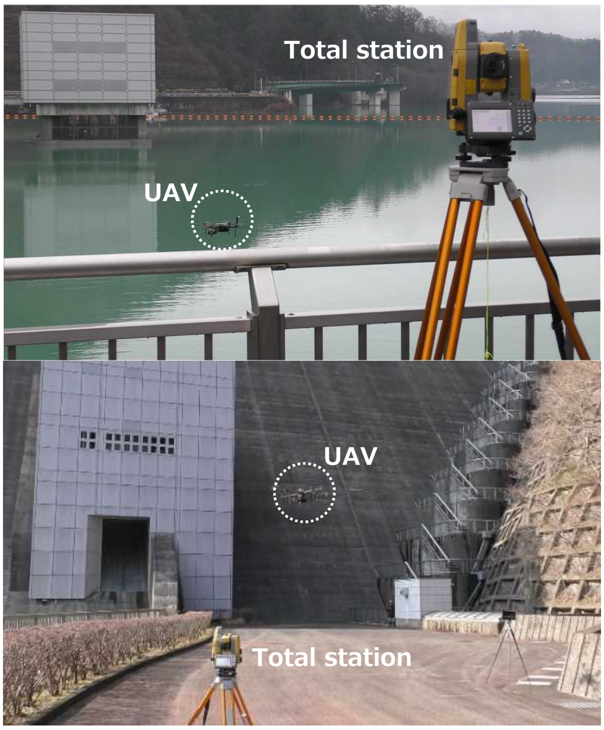

Figure 6. The flying UAV and tracking by the total station (Dam-1). The above image shows the tracking from above and the image below shows tracking from below.

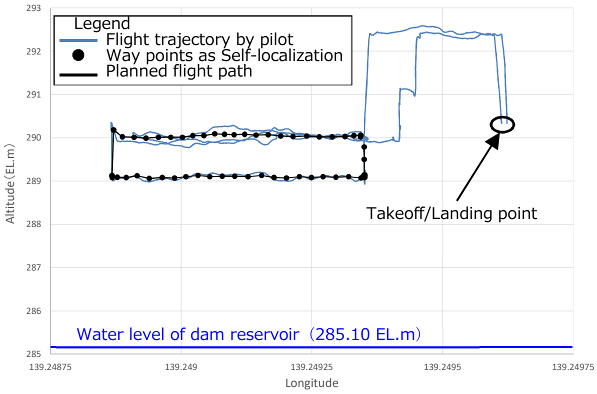

Figure 7. The WP results and the planned flight path using the manual flight trajectory (upstream side of the dam body at Dam-1). The blue line shows the manual flight trajectory of the UAV by tracking using the total station. The black marker indicates the self-estimated position as a WP and the black line shows the planned flight path for inspection.

4.2 Autonomous Flight Accuracy

Figure 9 shows a comparison of the WPs and flight trajectory for autonomous UAV flight. It can be verified that autonomous UAV flight is conducted with high accuracy, even if the vertical direction of the levee gradually thickens from top to bottom and has a complicated shape with horizontally curved lines.

In addition, the difference in distance between 228 WPs and autonomous flight coordinates is summarized in Figure 8. The maximum deviation distance was 0.90 m, the minimum was 0.03 m, and the median was 0.29 m; 90 % of the distance was covered within a deviation of 0.50 m. This flight accuracy is impossible with manual operation.

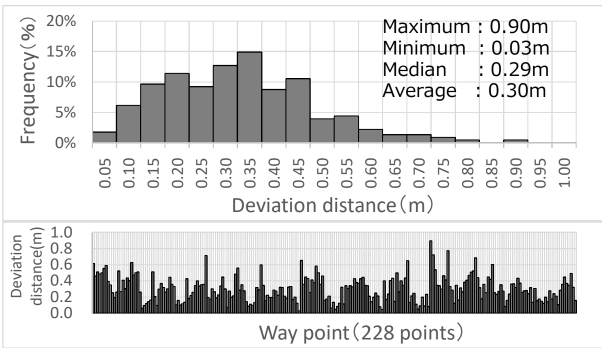

Figure 8. The distance difference frequency distribution between 228 waypoints and autonomous flight coordinates (Dam-2).

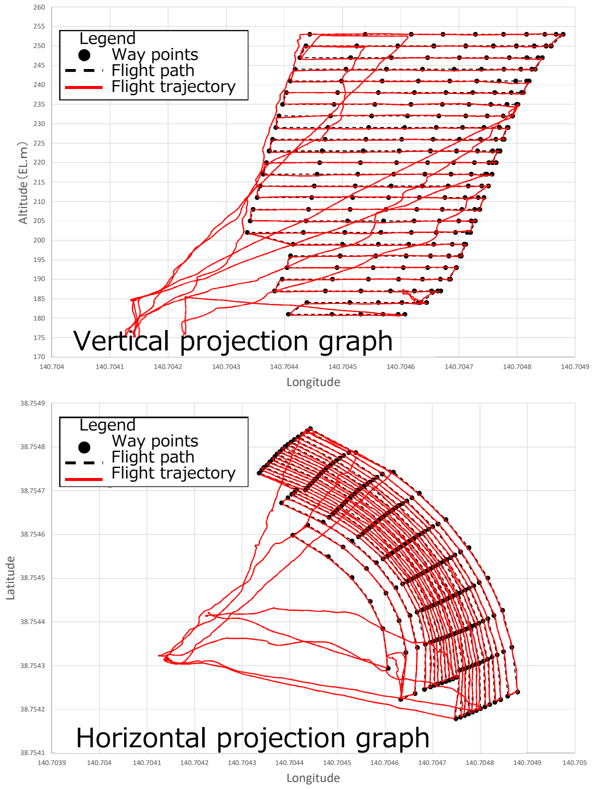

Figure 9. Comparison of WPs and flight trajectory for autonomous UAV flight (Dam-2). The black marker indicates the WPs. The black line shows the planned flight path for inspection. The red line shows the flight trajectory of the autonomous UAV flight.

4.3 Image Quality and Three-Dimensional Reconstruction Accuracy

Figure 10 shows an example of a dam body surface image taken via autonomous UAV flight. Although the absolute width and length could not be measured from the images obtained, it was possible to capture images with a resolution of approximately 1.75 mm/pixel as the vertical joint spacing of the dam is 2,000 mm.

In addition, a three-dimensional model is reconstructed using the SfM software Metashape, as shown in Figure 11. The difference between the three-dimensional point cloud data created by the two different flights was 0.255 mm in the horizontal direction and 0.203 m in the vertical direction; the shape of the dam body was not significantly distorted. As shown in Figure 12, it is confirmed that the use of geotags measured at the total station improved the photograph's alignment. Moreover, this stable and autonomous flight enabled the capture of clear and uniform images; furthermore, the feature point matching between the images taken from two different points is dense and good, as shown in Figure 13.

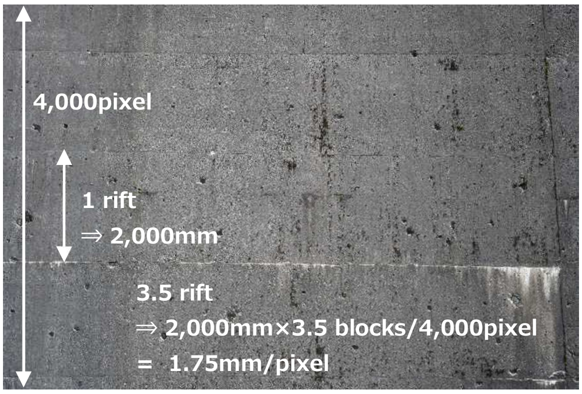

Figure 10. Accuracy verification of image (Dam-1)

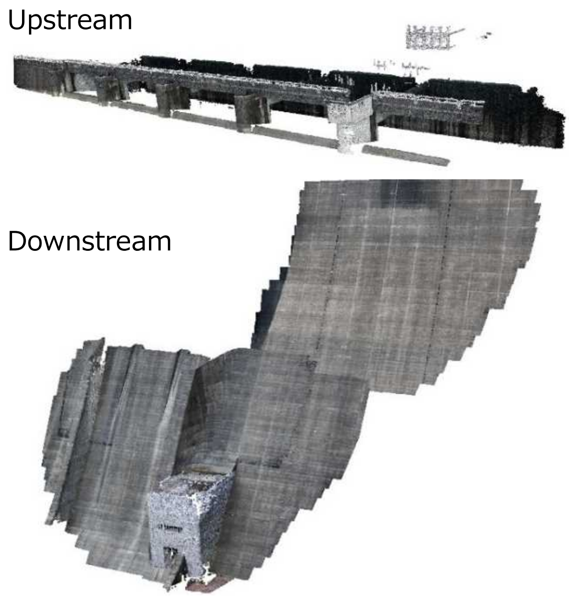

Figure 11. The result of the three-dimensional reconstruction model (Dam-2). The above image shows the view from upstream of the dam body. The image below shows the view from downstream of the dam body.

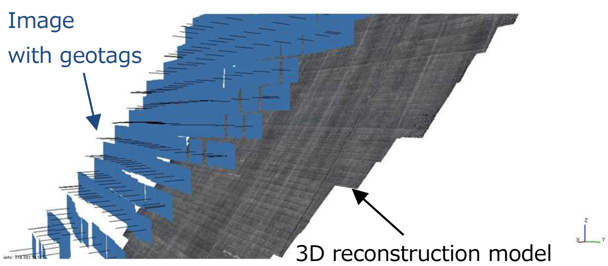

Figure 12. An example of the photograph's alignment (Dam-2).

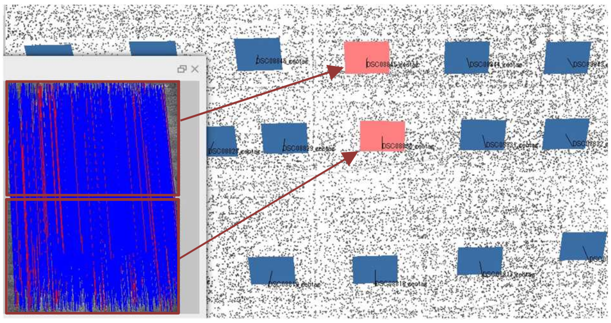

Figure 13. An example of feature point matching between images taken from two different points. The blue lines are a valid match. The red lines are an invalid match (Dam-2).

5 Proposed Flight Opportunity for Aging Detection Using AI Analysis

There are two methods for detecting dam surface aging via AI analysis: supervised and unsupervised learning.

Supervised learning is a method that enables AI to detect even unknown images by learning the teacher information with aging information annotations. Thus, this method is useful only if the observed aging target is obvious as only the annotated teacher information can be detected.

Conversely, unsupervised learning is a method in which AI learns the concept of a normal state and detects information when changes or abnormalities appear. As shown in Figure 14, it is possible to reconstruct a healthy image from a real damaged image and extract the damage from the difference.

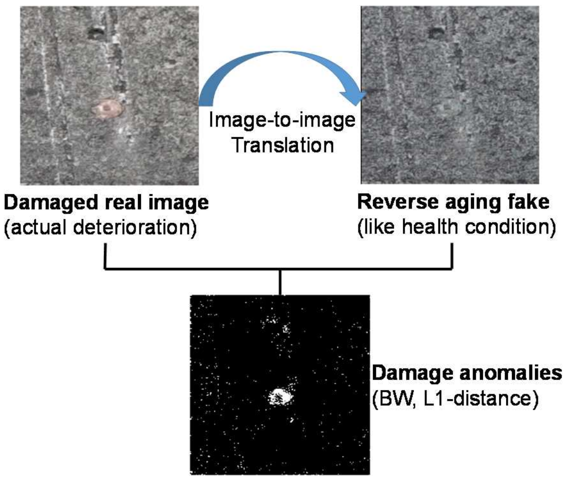

Figure 14. The unsupervised learning image (Dam-2)

There are few abnormal data points on the dam body and it is necessary to extract the various abnormal aging information from a wide range of dam bodies. Thus, unsupervised learning is suitable for the aging detection of dams. Therefore, it is necessary to accumulate images of the dam body during normal times, with uniform quality and accuracy. However, flight opportunities are limited because the dam inspection cycle is very long, i.e., once every few decades. Therefore, using the system proposed in this paper facilitates effective flight and imager accumulation.

6 Conclusion and Future Work

This paper proposes autonomous UAV flight using the dam's total station in non-GNSS environments. In addition, a flight path planning method based on the UAV's flight position, using a total station and geotags that can be added to the image by measuring the flight position at which the image is taken using the total station, which tracks the UAV, is proposed to obtain uniform quality and clear high-resolution images for inspection and management of the dam's body via a digital camera mounted on the UAV.

We implemented a field study and demonstrated the utility of the proposed approach. As a result, we could achieve a high flight accuracy, which is impossible via manual operation. Furthermore, we proposed flight opportunities for aging detection using AI analysis.

Future work is summarized as follows:

- Many field demonstrations will be conducted to verify its practicality.
- To sufficiently reduce the error in three-dimensional reconstruction accuracy, it is necessary to verify the accuracy by changing the lap ratio of the image and correcting it with GCP.
- It is necessary to accumulate images of the dam body surface during normal times.

References

[1] Cheng-Hsuan Yang, Ming-Chang Wen, Yi-Chu Chen, Shih-Chung Kang. An Optimized Unmanned Aerial System for Bridge Inspection. In *Proceedings of the 32nd ISARC*, pages 1–8, Oulu, Finland, 2015.

[2] Manh Duong Phung, Van Truong Hoang, Tran Hiep Dinh, Quang Ha. Automatic Crack Detection in Built Infrastructure Using Unmanned Aerial Vehicles. In *Proceedings of the 34rd ISARC*, pages 823–829, Taipei, Taiwan, 2017.

[3] Henk Freimuth, Jan Müller, Markus König. Simulating and Executing UAV-Assisted Inspections on Construction Sites. In *Proceedings of the 34rd ISARC*, pages 647–654, Taipei, Taiwan,

2017.

[4] Takato Yasuno, Junichiro Fujii, Masazumi Amakata. Pop-outs Segmentation for Concrete Prognosis Indices using UAV Monitoring and Dense Dilated Convolutions, In *Proceedings of 12th International Workshop on Structure Health Monitering*, pages 3175, California, USA, 2019.

[5] DJI. DJI GS PRO. On-line: https://www.dji.com/jp/ground-station-pro, Accessed: 15/6/2020.

[6] Jeonghoon Kwak and Yunsick Sung. Autonomous UAV Flight Control for GPS-Based Navigation. *IEEE Access*, 6:37947–37955, 2018.

[7] jitsuta. Drone navigation system (TS drone). On-line: https://www.jitsuta.co.jp/pickup/drone, Accessed: 15/6/2020.

[8] Alexis Stoven-Dubois, Laurent Jospin, Davide A. Cucci. Cooperative Navigation for an UAV Tandem in GNSS Denied Environments. In *Proceedings of 31st International Technical Meeting of the Satellite Division of the Institute of Navigation*, pages 2334–2339, Florida, USA, 2018.

[9] Cledat, E. and Cucci, D.A. Mapping GNSS Restricted Environments with a Drone Tandem and Indirect Position Control. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, IV-2/W3:1–7, 2017.