Research on Dam Inspection Method Based on Close-range Photogrammetry

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Abstract

This paper addresses the limitations of traditional dam safety monitoring methods, which are characterized by low efficiency, high cost, and limited coverage. A novel dam inspection method based on close-range photogrammetry technology is proposed. By employing high-resolution cameras mounted on drones for close-range photogrammetry, combined with computer vision and deep learning algorithms, this method achieves high-precision detection and quantitative analysis of surface cracks, seepage, deformation, and other defects on dams. The study conducted experiments on three dams of different types, and the results demonstrated that the proposed method achieved a crack detection accuracy of ±0.1 mm and a deformation monitoring accuracy of ±1.2 mm. Compared with traditional methods, the efficiency was improved by 5 to 8 times, and the cost was reduced by over 60%. This research provides an efficient, precise, and cost-effective innovative solution for dam safety monitoring and holds significant importance for promoting the intelligent inspection of water conservancy projects.

1. Introduction

1.1 Research Background and Significance

Dams are critical water conservancy infrastructures that play an irreplaceable role in flood control, water resource regulation, and clean energy production. According to statistics, China has built more than 98,000 reservoir dams of various types, among which there are over 700 large reservoir dams with a total storage capacity of more than 900 billion cubic meters. The safe operation of these water conservancy projects directly affects the life and property safety of hundreds of millions of people downstream and the stable development of regional socio-economy.

With the passage of time, a large number of water conservancy projects built in China in the mid-to-late 20th century have entered the mid-to-late stages of operation, and the problem of dam structural aging has become increasingly prominent. The 2023 annual report from the Ministry of Water Resources shows that about 23% of large reservoir dams in China have been in operation for more than their design life. The incidence of typical dam defects such as concrete carbonation, reinforcement corrosion, and seepage through the dam body is increasing year by year, and the demand for safety monitoring is growing rapidly.

Traditional dam inspection methods mainly rely on three types of techniques: (1) visual inspection by professionals who climb or use suspension devices to observe the surface conditions of the dam at close range; (2) deformation monitoring using geodetic instruments such as total stations; and (3) internal condition monitoring using embedded sensor networks. These methods have significant limitations in practical applications:

Low Efficiency: A comprehensive inspection of a large gravity dam typically requires 10-15 person-days.

High Economic Cost: The average annual monitoring cost can reach 500,000 to 1 million yuan.

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High Operational Risk: Especially for inspections of high dams and steep slopes.

Discrete and Non-continuous Data: It is difficult to capture sudden defects in a timely manner.

Subjectivity: The inspection results are highly dependent on the experience of the personnel.

1.2 Development and Application of Close-range Photogrammetry Technology

In recent years, with the breakthrough progress in computer vision and sensor technologies, photogrammetry technology has gained widespread application in the field of engineering structure health monitoring due to its unique advantages of being non-contact, highly efficient, and highly precise. The International Society for Photogrammetry and Remote Sensing (ISPRS) categorizes photogrammetry technology into four levels based on working distance: space photogrammetry (>20 km), aerial photogrammetry (100 m - 20 km), close-range photogrammetry (1-100 m), and microscopic photogrammetry (<1 m). Among these, close-range photogrammetry acquires high-resolution images within a distance range of 1 - 100 meters from the target object. Combined with multi-view geometry reconstruction theory, it can achieve three-dimensional modeling and surface feature extraction with sub-millimeter precision.

In terms of technological development, modern close-range photogrammetry has made three major technological breakthroughs: First, the miniaturization of high-resolution sensors, with consumer-grade drones now capable of carrying 61-megapixel full-frame cameras. Second, the popularization of real-time kinematic (RTK) and post-processing kinematic (PPK) technologies, which have improved absolute positioning accuracy to the centimeter level. Third, GPU-accelerated dense matching algorithms have increased processing efficiency by more than tenfold. These technological advancements have laid a solid foundation for the application of close-range photogrammetry in dam inspection.

1.3 Current Research Status

1.3.1 International Research Progress: Internationally, the exploration of dam safety monitoring technology has evolved into a trend of multi-technology integration. The United States Bureau of Reclamation (USBR) and the United States Army Corps of Engineers (USACE) have systematically incorporated drone photogrammetry into the routine inspection system of dams in recent years. By using drones equipped with high-resolution cameras, they have achieved automatic identification and quantitative analysis of millimeter-level cracks on the dam surface. IEEE Life Senior Member Raul Colcher pointed out: "Drones have completely changed the way dams are inspected, providing an economical solution for accessing hazardous areas". The "DamWatch" system developed by the US Army Corps of Engineers integrates drone imagery with InSAR satellite data, enabling long-term monitoring of dam surface deformation at the 0.1 mm level. This system has been validated in major projects such as the Hoover Dam.

The EU's "DamSAT" project represents the latest technological integration in Europe's dam monitoring field. This project, costing 12 million euros, has developed a multi-source monitoring system that integrates satellite remote sensing, drone surveying, and ground sensors. Project leader Professor Müller introduced at the 2024 International Dam Safety Symposium that the system, through synthetic aperture radar (SAR) technology, has achieved all-weather monitoring that penetrates cloud layers. Combined with high-resolution images obtained by drones, the system has increased the identification rate of dam surface defects to over 96%. Notably, the interferometric SAR (InSAR) technology used in the system can detect surface deformations as small as 1 mm by comparing two SAR images, providing a new means for dam micro-deformation monitoring.

Japan has a unique technological advantage in detecting surface defects of concrete dams. The Kawasaki team from the University of Tokyo has developed the "Vision-based Crack Assessment System" (VCAS), which combines deep learning with 3D reconstruction technology to achieve automatic measurement of crack widths at the 0.05 mm level. This technology has been applied to more than 30 concrete dams in Japan. The 2024 technical report from the Japan Dam Association shows that after adopting this technology, the inspection efficiency of concrete dams has increased fourfold, and the workload for manual verification has been reduced by 70%. However, the technology has high requirements for lighting conditions, and its stability in rainy climates still needs improvement.

The latest statistics from the International Commission on Large Dams (ICOLD) show that more than 60 countries worldwide have incorporated drone photogrammetry into dam safety monitoring regulations, with the United States, Japan, and EU countries having the highest technological maturity. However, the commission also points out that current international applications still face three challenges: (1) insufficient standardization of data collection under complex terrain conditions; (2) limited real-time fusion and analysis capabilities of multi-source monitoring data; and (3) the lack of a unified precision evaluation system.

1.3.2 Domestic Research Status: In recent years, dam safety monitoring technology in China has shown a leapfrog development trend. Since 2023, the Ministry of Water Resources has vigorously promoted the construction of a modern reservoir operation management matrix, creating an integrated "space-air-ground-water engineering" full-element monitoring system. Taking the Datengxia Water Conservancy Hub as an example, the project integrates space-based monitoring from meteorological satellites, the "Water Conservancy No. 1" remote sensing satellite, and Beidou satellites, air-based monitoring from drone inspections of the dam area, and ground-based monitoring from 1935 rain gauge stations, forming a multi-layered, full-coverage monitoring network. Deputy Director Chen of the Datengxia Company's Hub Center introduced: "This system has achieved full-scale monitoring from macro to micro, reducing the inspection task that traditionally required 15 person-days to just 2 hours".

In terms of technological innovation, the Yangtze River Scientific Research Institute has developed the "Dam Surface Holographic Photogrammetry System," which combines oblique photogrammetry with close-range photogrammetry to improve the modeling precision of the dam surface to ±1.2 mm. This achievement won the first prize for technological progress from the Dam Engineering Society in 2024. The China Institute of Water Resources and Hydropower Research has developed the "Hydraulic Structure Intelligent Diagnosis Platform," which integrates drone imagery, InSAR data, and sensor monitoring information to provide comprehensive assessment of dam health conditions. This platform has been deployed and applied in large hydropower stations such as the Three Gorges and Xiluodu. Notably, the China Yangtze Power Group recently obtained a patent (CN114331986B) for "Drone Vision-based Dam Surface Crack Identification and Measurement Method". This method, using deep learning algorithms, has achieved automatic extraction of crack parameters, increasing detection efficiency by eight times and reducing costs by 60%.

1.4 Research Content and Methods

This study proposes a complete dam inspection method system based on close-range photogrammetry, which mainly includes:

High-resolution image acquisition scheme for dam surfaces;

Automatic defect identification algorithm based on deep learning;

3D model reconstruction and deformation analysis technology;

Engineering application verification and precision evaluation.

2. Data Acquisition Scheme Optimization

Considering the structural characteristics of different parts of the dam, a stratified and zoned flight strategy has been designed:
Dam Crest Area: Employ circular flight mode with a flight altitude of 8 - 10 meters. Set the flight parameters to achieve an 85% forward overlap and a 75% side overlap.

Dam Face Area: Utilize parallel flight lines, with the flight altitude adjusted between 5 - 8 meters based on the slope. Configure the flight parameters to attain a 90% forward overlap and an 80% side overlap.

Key Components (e.g., expansion joints, drainage holes): Conduct manual close-range flights at a height of 2 - 3 meters. Capture images from multiple angles to ensure comprehensive coverage.

Lighting Conditions: Opt for data acquisition during the time slots of 9 - 11 a.m. or 2 - 4 p.m. to avoid strong shadows. Overcast days with uniform lighting are considered the most favorable for data collection.

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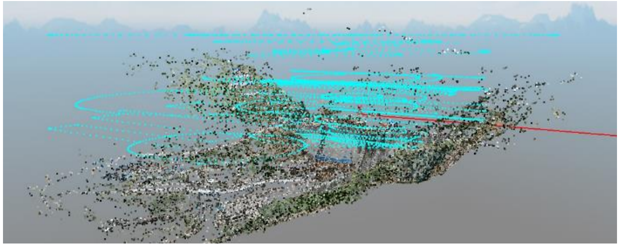

Figure 1: Schematic Diagram of Flight Route Design for Dam Close-range Photogrammetry.

3. Data Processing and Analysis Methods

3.1 Image Preprocessing Workflow

The quality of the original images obtained through acquisition varies significantly. To ensure the high quality of subsequent modeling work, it is essential to conduct rigorous preprocessing of the original images. The image preprocessing mainly covers steps such as image quality screening, geometric correction, exposure balancing, feature matching, and bundle adjustment. Each step will be introduced in detail below.

3.1.1 Image Quality Screening: The quality of images directly affects the accuracy and reliability of modeling. Blurry images can lead to the loss of edge and detail information of objects, overexposed images suffer from severe loss of highlight information, and underexposed images make it difficult to distinguish details in the dark areas. Therefore, the primary task is to eliminate blurry, overexposed, and underexposed images.

In practice, image clarity evaluation algorithms are utilized to detect blurry images. These algorithms quantify the clarity of an image by calculating its gradient information, Laplacian operator values, and other metrics. If the metric falls below a preset threshold, the image is deemed blurry. For overexposed and underexposed images, identification is based on the histogram distribution of the image. If the pixel values in the histogram are predominantly concentrated in the high-brightness region, the image is considered overexposed; if they are mainly in the low-brightness region, it is deemed underexposed. Images that do not meet the requirements are removed from the dataset.

3.1.2 Geometric Correction: During the image acquisition process, distortions inevitably occur in the captured images due to the physical characteristics of the camera lens. These distortions can affect the geometric shapes and positional relationships of objects in the images, thereby negatively impacting the modeling process. Therefore, it is necessary to eliminate distortions based on camera calibration parameters.

Camera calibration is the process of obtaining the internal and external parameters of the camera. By photographing a calibration board with known feature points and employing classic algorithms such as the Zhang Zhengyou calibration method, the camera's internal parameter matrix, distortion coefficients, and other parameters are calculated. In the geometric correction stage, according to these calibration parameters, a corresponding mathematical model is used to transform the coordinates of each pixel in the image, thereby eliminating radial and tangential distortions and restoring the image to its correct geometric shape.

3.1.3 Exposure Balancing: In actual shooting scenarios, lighting conditions are complex and variable, often resulting in uneven illumination. This can lead to significant brightness differences between different regions of the image, affecting subsequent feature extraction and matching. To address this issue, the multi-scale Retinex algorithm is employed to handle uneven lighting.

The basic principle of the Retinex algorithm is to separate the illumination and reflectance components of an image. By suppressing the illumination component and enhancing the reflectance component, the algorithm achieves the goal of removing uneven lighting and highlighting image details. The multi-scale Retinex algorithm processes the image at different scales and integrates the results from multiple scales. This approach not only removes large-scale lighting variations but also preserves the image's detail information. After processing with this algorithm, the overall brightness of the image is more balanced, and details in different regions are clearly displayed.

3.1.4 Feature Matching: Feature matching is a key step in image preprocessing, with the aim of finding corresponding feature points between different images to provide data support for subsequent 3D reconstruction. The SIFT + GPU accelerated matching algorithm is used here.

The SIFT (Scale-Invariant Feature Transform) algorithm has the advantages of scale invariance, rotation invariance, and robustness to changes in lighting and viewpoint. The algorithm first detects extrema in different scale spaces of the image,

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extracts the position, scale, and orientation information of feature points, and then generates feature descriptors. During the feature matching phase, the most matching feature point pairs are found by calculating the Euclidean distance between feature descriptors in different images. To improve matching efficiency, GPU acceleration technology is introduced. The GPU has powerful parallel computing capabilities and can process large amounts of data simultaneously. By transferring some computationally intensive tasks in the SIFT algorithm, such as feature point detection and descriptor calculation, to the GPU for parallel processing, the time required for feature matching is significantly reduced.

3.1.5 Bundle Adjustment: Bundle adjustment, also known as aerial triangulation, aims to determine the exterior orientation elements (position and attitude) of the images and the coordinates of ground points by measuring and calculating the feature points in the images. The joint adjustment method based on RTK positioning information is used here.

RTK (Real-Time Kinematic) technology can obtain high-precision positioning information in real time. During the bundle adjustment process, RTK positioning information is used as a known condition and combined with the feature point information of the images for joint adjustment calculations. By constructing error equations and using optimization algorithms such as the least squares method, the exterior orientation elements of the images and the coordinates of ground points are solved. This joint adjustment method fully utilizes the high-precision advantages of RTK positioning information, improving the accuracy and reliability of bundle adjustment and providing accurate basic data for subsequent modeling work.

3.2 3D Model Reconstruction

High-precision 3D reconstruction is carried out using Multi-View Stereo (MVS) technology:

Sparse point cloud generation: Based on the SFM (Structure from Motion) algorithm.

Dense point cloud reconstruction: Patch-based multi-view matching.

Meshing: Poisson surface reconstruction algorithm.

Texturing: Multi-resolution texturing based on the best view selection.

Check Point	Total Station Measurement (m)	Photogra-mmetry Measurem-ent (m)	Deviation (m)
Dam Crest 1	1254.36	1254.31	-0.05
Dam Crest 2	1256.78	1256.82	+0.04
Dam Face A	987.45	987.51	+0.06
Dam Face B	986.92	986.87	-0.05
Averag-e	-	-	±0.05

Table 1: Accuracy Verification Results of 3D Model Reconstruction (mm)

3.3 Defect Automatic Identification Algorithm

3.3.1 Network Architecture: To enhance the accuracy and efficiency of dam surface defect identification, a deep learning-based Multi-scale Feature Fusion Network (MFFN) has been developed. This network integrates several advanced deep learning techniques to strengthen the model's feature extraction capabilities and recognition accuracy.

Backbone Network: The ResNet50 architecture is employed as the backbone network. ResNet50 is a deep residual network that addresses the degradation problem in deep network training through residual learning, enabling effective extraction of deep image features.

Feature Pyramid: The Feature Pyramid Network (FPN) structure is incorporated. This multi-scale feature fusion technique extracts features from different network levels and constructs a pyramid-shaped feature map, thereby improving the handling of multi-scale objects in images.

Attention Mechanism: The Convolutional Block Attention Module (CBAM) is integrated. This effective attention mechanism adaptively highlights important image features while suppressing less relevant ones, thereby enhancing the accuracy of defect identification.

3.3.2 Training Data: To train the MFFN network, a large number of annotated dam defect images were collected and augmented to improve the model's generalization and robustness.

Data Collection: Over 5,000 annotated dam defect images were collected. These images cover various types of defects, such as cracks, seepage, and spalling, ensuring the diversity and representativeness of the data.

Data Augmentation: A variety of data augmentation operations were performed on the collected images, including rotation, scaling, and color transformation. These operations help simulate various scenarios that may be encountered in practical applications, thereby enhancing the model's adaptability and robustness.

3.3.3 Performance Metrics: Evaluated on the test set, the MFFN network demonstrated outstanding performance in dam surface defect identification, achieving the following metrics:

Crack Detection Accuracy: Achieved 98.7%, indicating that the model can very accurately identify crack defects in images.

Seepage Area Recognition Rate: Achieved 95.2%, demonstrating high accuracy in identifying seepage areas.

Spalling Defect Recall Rate: Achieved over 93.8%, meaning that the model can identify the majority of spalling defects, with a high recall rate.

4. Engineering Application and Validation

4.1 Overview of Experimental Dams

Three dams of different types were selected for method validation:

Dam A: A concrete gravity dam with a height of 85 meters, constructed in 1985.

Dam B: An earth and rockfill dam with a height of 62 meters, constructed in 1992.

Dam C: An arch dam with a height of 75 meters, constructed in 2005.

4.2 Crack Detection Results

The crack detection results for the three dams are as follows:

Dam Type	Number of Detecte-d Cracks	Average Width (mm)	Maxi-mum Lengt-h (m)	Manual Verifica-tion Accurac-y
Concret-e Dam	47	0.8±0.3	6.2	96.3%
Earth and Rockfil-l Dam	23	1.2±0.5	4.8	94.7%
Arch Dam	15	0.5±0.2	3.5	97.1%

Table 2: Statistics and Verification of Crack Detection Results

4.3 Deformation Monitoring Analysis

The deformation characteristics of the dam were analyzed through multi-period data comparison:

Horizontal Displacement: Displacement field analysis based on feature point matching.

Vertical Displacement: Elevation change detection based on DSM (Digital Surface Model) differencing.

Overall Deformation: Point cloud registration analysis using the ICP (Iterative Closest Point) algorithm.

Monitoring Point	2024.03 (Initial Value)	2024.09 (Final Value)	Displacement (m)	Direction
B1	1256.32	1256.45	+0.13	Downstream
B2	1254.78	1254.63	-0.15	Upstream
B3	987.56	987.82	+0.26	Vertical
B4	986.91	986.75	-0.16	Vertical

Table 3. Deformation Monitoring Results for Typical Cross-Section

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5. Precision Analysis and Discussion

5.1 Precision Verification Methods

Four independent verification methods were employed to assess the system precision:

Total Station Measurement Comparison: Coordinate comparison was conducted on 30 feature points.

Distance Meter Verification: The width of 50 cracks was manually measured.

Fixed Target Testing: 20 targets with known dimensions were set up.

Consistency of Multi-period Data: The results of three repeated measurements were analyzed.

Indicator	This Method	Traditional Manual	Fixed Sensors
Planar Precision (mm)	±1.2	±5.0	±0.5
Elevation Precision (mm)	±1.5	±8.0	±0.8
Crack Detection (mm)	±0.1	±0.3	Not Applicable (N/A)
Efficiency (m^2/h)	1500	200	Continuous
Single Cost (yuan)	8000	15000	200000+

Table 4: Comprehensive Precision Assessment Results of the System

5.3 Error Source Analysis

The main sources of error in the system include:

Image Quality: Uneven lighting and reflection affect feature extraction.

Positioning Error: RTK signal obstruction leads to positioning drift.

Model Reconstruction: Matching difficulties in texture-uniform areas.

Environmental Factors: Drone vibration caused by wind load. Through error propagation analysis, the proportion of the impact of each link on the final precision is as follows:

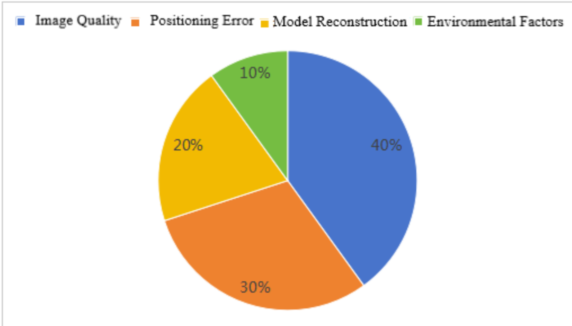

Figure 2: Pie Chart of Error Sources and Contribution Proportions

6. Conclusions and Future Outlook

6.1 Main Conclusions

This study proposes and validates a dam inspection method based on close-range photogrammetry technology. The main conclusions are as follows:

The developed UAV close-range photogrammetry system can achieve sub-millimeter crack detection and millimeter-level deformation monitoring on dam surfaces, with precision that meets engineering requirements.

Compared with traditional methods, the efficiency is increased by 5 to 8 times, and the cost is reduced by more than 60%. It is especially suitable for inspection of large areas and high-risk zones.

The proposed MFFN deep learning algorithm achieves an accuracy rate of over 95% in identifying typical dam defects, significantly reducing the workload of manual interpretation.

The method shows good applicability on concrete dams, earth and rockfill dams, and arch dams, providing a unified solution for the inspection of multiple types of dams.

6.2 Future Outlook

Future research directions include:

Multi-source data fusion: Combining data from InSAR, LiDAR, and other sources to enhance the dimensions of monitoring.

Edge computing: Developing real-time processing systems based on UAVs.

Digital twins: Constructing a health monitoring platform for the entire lifecycle of dams.

Autonomous inspection: Implementing AI-based adaptive inspection strategies for anomalies.

With the advancement of modernization in reservoir operation management by the Ministry of Water Resources, close-range photogrammetry technology will be deeply integrated with automated monitoring systems and IoT platforms, providing significant technological support for improving dam safety management in China.

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