



Research on Bridge Alignment Extraction and Measurement Method Based on UAV Vision

Jing Cai¹, Lei Zhang², Zhiqiang Xu³

Xinjiang Municipal Rail Transit Co., Ltd., Wulumuqi 830000, Xinjiang, China

Abstract: Bridge alignment measurement during construction is an important means to ensure construction quality and structural safety. Although traditional contact-based measurement methods provide high accuracy, they suffer from low efficiency, high operational risk, and poor operability. UAV vision-based measurement, as a non-contact technique, offers advantages such as simple operation, high safety, and rapid data acquisition; however, it still faces challenges in measurement accuracy, methodological completeness, and adaptability to on-site conditions. Therefore, in-depth research on UAV vision-based bridge alignment extraction and measurement has significant theoretical value and promising engineering application prospects.

Keywords: UAV vision, bridge construction, alignment measurement, sub-pixel edge detection

1. Introduction

Traditional bridge construction monitoring methods mainly rely on manual observation and conventional instruments, which are insufficient to meet the requirements of high precision, real-time performance, and efficiency for long-span bridge construction.

In particular, due to the multiple deformation factors and complex construction environment of long-span bridges, traditional monitoring methods exhibit obvious limitations under dynamically changing conditions. In recent years, with the rapid development of UAV technology, its applications have expanded from conventional fields such as surveying, transportation, monitoring, and military uses to emergency mapping, industrial inspection [1], natural disaster monitoring[2], vegetation investigation[3], and urban safety management[4].

Numerous studies have focused on developing UAV-based displacement measurement technologies and have achieved remarkable progress in recent years[5–15].

Wells and Lovelace demonstrated that bridge inspection projects using UAV systems can save approximately 60% of the cost compared with traditional inspection techniques[16–19].

2. Bridge Alignment Extraction Method Based on UAV Vision

In image edge detection, conventional pixel-level methods are limited by discrete pixel resolution and cannot accurately capture subtle edge variations.

The gradient interpolation method can effectively improve detection accuracy and compensate for the deficiencies of pixel-level edge detection.

2.1 UAV Image Acquisition and Camera Calibration

Prior to image acquisition, camera calibration is required to eliminate systematic errors in the imaging process.

An asymmetric circular calibration board was adopted in this study to improve the robustness of corner extraction.

Compared with conventional symmetric patterns, the asymmetric calibration target exhibits superior stability in feature extraction and matching reliability.

The camera calibration procedure was conducted using the Camera Calibrator toolbox in MATLAB, which automatically detects calibration patterns and extracts corner coordinates.

By accurately locating these feature points, the intrinsic camera matrix and lens distortion parameters were estimated.

A total of 20 groups of calibration images were collected and processed in this experiment.

The results show that the average reprojection error was 0.39 pixels and the focal length was 13 mm, indicating satisfactory calibration accuracy (Figure 1).

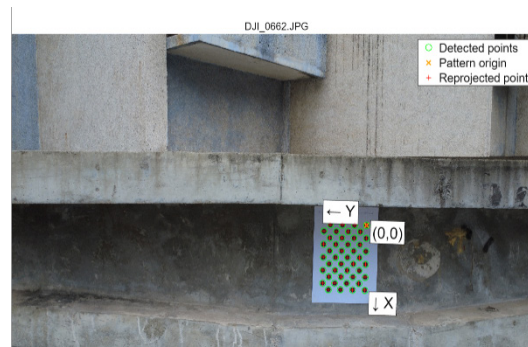


Figure 1. Corner extraction results

The optical parameter matrix is shown in the formula below.

$$K = \begin{bmatrix} 5911.4 & 0 & 1893.1 \\ 0 & 5925.3 & 963.9257 \\ 0 & 0 & 1 \end{bmatrix}$$

2.2 Multi-view Image Registration and Stitching

To reduce stitching errors, all images were corrected for lens distortion using the intrinsic parameters obtained from camera calibration. Radial and tangential distortion coefficients were employed to remap the original images and restore the true geometry of the bridge model. During UAV translational flights, slight variations in flight altitude, shooting angle, and camera settings inevitably introduce geometric deviations between adjacent images.

Because it is difficult to maintain a strictly orthographic pose during flight, the captured images usually suffer from angular displacement, geometric deformation, and alignment mismatches.

If these errors are not corrected, they will significantly reduce the accuracy of image stitching. Therefore, projective transformation was adopted to perform geometric correction and enhance image registration accuracy.

After projection transformation, relative orientation was introduced to establish accurate spatial correspondence between the reference image and the translated images. The Scale-Invariant Feature Transform (SIFT) algorithm was used to extract distinctive feature points from the images.

To further improve the reliability of feature matching, the Random Sample Consensus (RANSAC) algorithm was applied to remove outliers and retain high-confidence correspondences for homography estimation.

As shown in Figure 2.

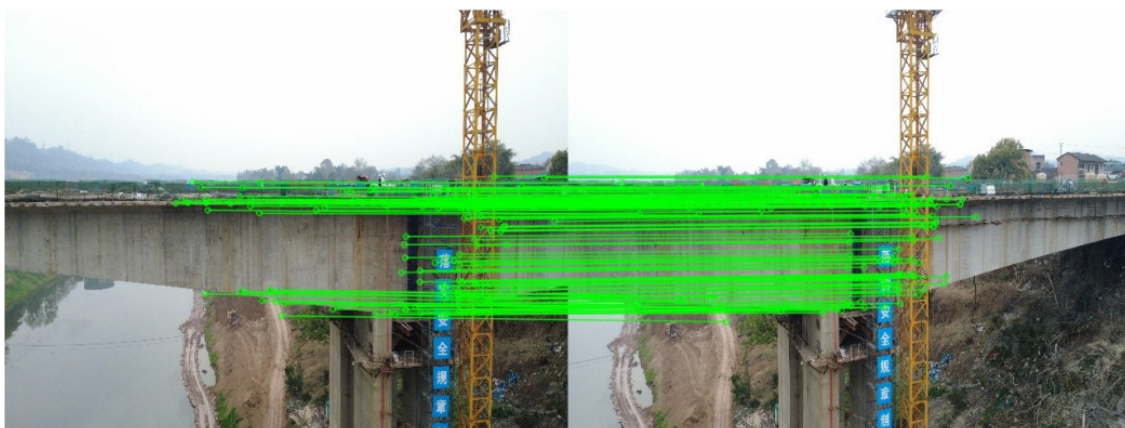


Figure 2. Feature point extraction

2.3 Sub-pixel Edge Detection and Alignment Extraction

The gradient interpolation method performs sub-pixel localization based on the assumption of linear gray-level variation in a local neighborhood. This method is computationally efficient but may introduce interpolation errors in regions

where the gray-level distribution is nonlinear. Moreover, it is highly sensitive to gradient estimation accuracy, and noise interference can directly affect edge positioning precision.

To address these issues, a hybrid algorithm combining the Canny edge detector with the gradient interpolation method was employed. The Canny operator provides stable and accurate pixel-level edge detection, while the gradient interpolation technique further refines edge positions at the sub-pixel level. This combined strategy significantly improves detection accuracy, noise resistance, and edge smoothness, making it particularly suitable for complex bridge structures.

3. Experimental Results and Analysis

3.1 Indoor Scaled Bridge Model Experiment

An indoor scaled experiment was carried out to verify the feasibility and accuracy of UAV image-based bridge alignment extraction. The test specimen was a continuous rigid-frame bridge model with a total length of approximately 6.2 m, a deck width of 0.6 m, and a pier height of 1.6 m, arranged in a two-span configuration. A steel box girder was installed at the mid-span to connect the hybrid beam system.

To evaluate the ability of the proposed method to identify subtle alignment changes, two sets of UAV flights were conducted under identical procedures, corresponding to the baseline condition and the mortar-loaded condition. By comparing the extracted alignments before and after mortar loading and incorporating the measured mortar thickness, the sensitivity of the image-processing algorithm to small deformation variations was assessed.

The experimental model is shown in Figure 3.



Figure 3. Bridge experimental scale model diagram

3.2 Field Validation During Construction of an Actual Bridge

To further verify the feasibility and accuracy of UAV image-based alignment measurement during bridge construction, the Zhiping Qihe Bridge was selected as the case study, and on-site alignment extraction and comparative measurements were conducted.

The field view of the bridge is shown in Figure 4.



Figure 4. Real view of Zhiping Qihe Bridge

The construction-stage alignment information of the Zhiping Qihe Bridge was obtained using a combination of UAV image acquisition and conventional leveling measurements. A total of 24 key control points were arranged within the same area, and their elevations were measured using a leveling instrument as reference values for alignment evaluation.

The elevations at the corresponding control points were extracted from the image-derived alignment, and the discrepancies between the two datasets were compared to analyze the accuracy and feasibility of the proposed image-based measurement method. To ensure data alignment and computational consistency, the midpoint of the bottom section of the 0# block was selected as the unified reference point to reduce baseline offset errors. The twelve points on the Luohuang side were

labeled as P₁–P₁₂, and the twelve points on the Zhiping side were labeled as Q₁–Q₁₂, where P₁ and Q₁ are located closest to the 0# block, and P₁₂ and Q₁₂ are located at the far ends of each side, as shown in Figure 5.

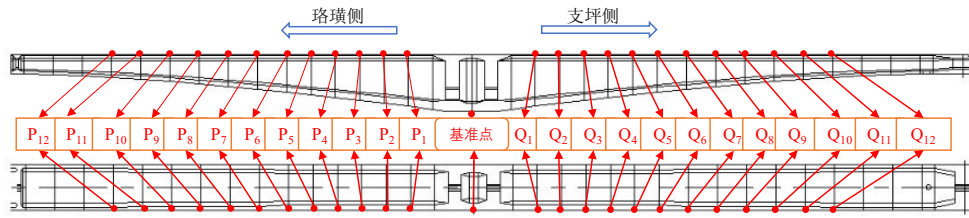


Figure 5. Bridge measuring point layout plan

Based on the bridge alignment data extracted by UAV imagery and the results of leveling measurements, the alignment accuracy of the construction segments is compared and analyzed. This paper uses the midpoint of the lower coordinate of concrete #0 as a unified reference point, and performs leveling measurements on the Luohuang side (P₁–P₁₀) and the Zhiping side (Q₁–Q₁₂), establishing a unified coordinate system. A schematic diagram of the leveling point establishment is shown in Figure 6, and the coordinates of the measured points are shown in Table 1.

The results indicate that the construction segment exhibits noticeable longitudinal elevation variation, with an obvious vertical low point near the 0# block, which reflects the structural stress state and alignment control characteristics during construction. Meanwhile, the elevation variation trends of all measurement points are generally consistent with the designed bridge alignment, demonstrating that leveling measurements can accurately capture the alignment characteristics of the bridge during construction.

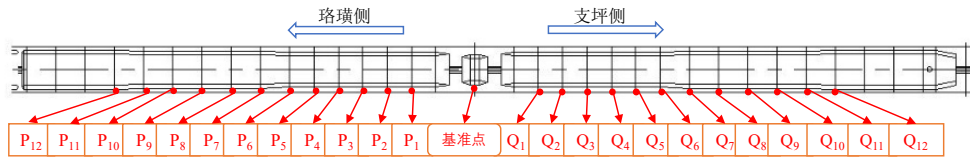


Figure 6. Leveling survey point layout diagram

Table 1. Leveling results

Leveling survey point		P12	P11	P10	P9	P8	P7
Leveling results	x(m)	-55.5	-51	-46.5	-42	-37.5	-33
	y(m)	223.122	223.030	223.002	222.958	222.930	222.925
Leveling survey point		P6	P5	P4	P3	P3	P1
Leveling results	x(m)	-28.5	-24.75	-21	-17.25	-13.5	-9.75
	y(m)	222.935	222.891	222.867	222.871	222.855	222.825
Leveling survey point		Q1	Q2	Q3	Q4	Q5	Q6
Leveling results	x(m)	9.75	13.5	17.25	21	24.75	28.5
	y(m)	222.707	222.710	222.694	222.676	222.666	222.638
Leveling survey point		Q7	Q8	Q9	Q10	Q11	Q12
Leveling results	x(m)	33	37.5	42	46.5	51	55.5
	y(m)	222.601	222.623	222.572	222.521	222.534	222.522

4. Conclusion

This study investigated bridge alignment measurement and accuracy verification during the construction stage based on UAV image technology, and systematically examined and validated the application of key techniques including camera calibration and distortion correction, image processing, feature extraction, and edge detection.

References

- [1] Morando L, Recchiuto C T, Calla J, et al. Thermal and visual tracking of photovoltaic plants for autonomous UAV inspection[J]. *Drones*, 2022, 6(11): 347.
- [2] Zhang Y, Chen S, Wang W, et al. Pyramid attention based early forest fire detection using UAV imagery[C]//*Journal of Physics: Conference Series*. IOP Publishing, 2022, 2363(1): 012021.
- [3] Carvajal-Ramírez F, Serrano J M P R, Agüera-Vega F, et al. A comparative analysis of phytovolume estimation methods based on UAV-photogrammetry and multispectral imagery in a mediterranean forest[J]. *Remote Sensing*, 2019, 11(21): 2579.
- [4] Skondras A, Karachaliou E, Tavantzis I, et al. UAV Mapping and 3D Modeling as a Tool for Promotion and Management of the Urban Space[J]. *Drones*, 2022, 6(5): 115.
- [5] Yoon H, Shin J, Spencer Jr B F. Structural displacement measurement using an unmanned aerial system[J]. *Computer-Aided Civil and Infrastructure Engineering*, 2018, 33(3): 183-192.
- [6] Zhang X, Zeinali Y, Story B A, et al. Measurement of three-dimensional structural displacement using a hybrid inertial vision-based system[J]. *Sensors*, 2019, 19(19): 4083.
- [7] Hoskere V, Park J W, Yoon H, et al. Vision-based modal survey of civil infrastructure using unmanned aerial vehicles[J]. *Journal of Structural Engineering*, 2019, 145(7): 04019062.
- [8] Ri S, Ye J, Toyama N, et al. Drone-based displacement measurement of infrastructures utilizing phase information[J]. *Nature Communications*, 2024, 15(1): 395.
- [9] Weng Y, Shan J, Lu Z, et al. Homography-based structural displacement measurement for large structures using unmanned aerial vehicles[J]. *Computer-Aided Civil and Infrastructure Engineering*, 2021, 36(9): 1114-1128.
- [10] Ribeiro D, Santos R, Cabral R, et al. Non-contact structural displacement measurement using Unmanned Aerial Vehicles and video-based systems[J]. *Mechanical Systems and Signal Processing*, 2021, 160: 107869.
- [11] Chen G, Liang Q, Zhong W, et al. Homography-based measurement of bridge vibration using UAV and DIC method[J]. *Measurement*, 2021, 170: 108683.
- [12] Sun J, Peng B, Wang C C, et al. Building displacement measurement and analysis based on UAV images[J]. *Automation in Construction*, 2022, 140: 104367.
- [13] Bolognini M, Izzo G, Marchisotti D, et al. Vision-based modal analysis of built environment structures with multiple drones[J]. *Automation in Construction*, 2022, 143: 104550.
- [14] Erdenebat D, Waldmann D. Application of the DAD method for damage localisation on an existing bridge structure using close-range UAV photogrammetry[J]. *Engineering Structures*, 2020, 218: 110727.
- [15] Zhang C, Zou Y, Wang F, et al. Towards fully automated unmanned aerial vehicle-enabled bridge inspection: Where are we at?[J]. *Construction and Building Materials*, 2022, 347: 128543.
- [16] Wells J, Lovelace B. Unmanned aircraft system bridge inspection demonstration project phase II final report[R]. Minnesota. Dept. of Transportation. Research Services & Library, 2017.
- [17] Hernandez I, Fields T, Kevern J. Overcoming the challenges of using unmanned aircraft for bridge inspections[C]// *AIAA Atmospheric Flight Mechanics Conference*. 2016: 3396.
- [18] Gillins D T, Parrish C, Gillins M N, et al. Eyes in the sky: Bridge inspections with unmanned aerial vehicles[R]. 2018.
- [19] Wells J, Lovelace B. Improving the quality of bridge inspections using unmanned aircraft systems (UAS)[R]. Minnesota. Department of Transportation, 2018.