

INTEGRATING CLOSE-RANGE PHOTOGRAMMETRY WITH DEEP LEARNING FOR INTELLIGENT 3D DOCUMENTATION OF CRACKS IN WIND-RAIN BRIDGE HERITAGE

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1. Introduction

Multi-source data fusion and other technical methods can effectively advance the construction of real-scene 3D. Multi-source data fusion primarily involves integrating oblique photography models with point cloud data, BIM models, close-range photography models, etc. This multi-source data fusion technology is applied to modern buildings in urban areas as well as ethnic architecture in traditional villages. Luo and Zhu [1-2] integrated oblique photography models with laser-scanned point cloud data to achieve city-level real-scene 3D modeling. Cai [3] proposed applying close-range photogrammetry and BIM technology to the real-scene 3D modeling of ethnic architecture in traditional villages, forming a 3D model database of ethnic architectural components to achieve the digital preservation of ethnic architecture and its building elements.

Nowadays, as the foundational framework for the Real-scene 3D of the city and countryside in China initiative has been put in place, the Ministry of Natural Resources continuously releases calls for innovative application cases to promote the high-quality development of real-scene 3D data. Therefore, it is imperative to empower high-quality scenario development through real-scene 3D. Relevant researchers have produced corresponding results in applications empowered by real-scene 3D. For instance, a multi-source heterogeneous data fusion model based on multiple sensors was proposed to form an urban-level digital twin spatial foundation in which they utilized high-rendering technology with Unreal Engine and streaming architecture to empower the application of real-scene 3D in urban management [4]. Xu [5] proposed using various forms such as sky-air-ground-interior based methods with real-scene 3D for stability

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detection of geological slopes. Additionally, a surface crack detection method for concrete structures based on 3D reconstruction was developed [6], which maps 2D crack identification results onto the corresponding 3D model. Thus, real-scene 3D models can enable the detection of apparent cracks in building structures.

However, existing research rarely involves the application of real-scene 3D in detecting cracks in brick-concrete structures within architectural heritage. The main reason is that automated detection of cracks in brick-concrete structures requires obtaining high-precision, high-resolution images of brick walls which, in turn, necessitates capturing images using a camera close to the brick wall structure. However, this shooting method yields image data covering only a small area of the brick wall, making it difficult to determine the actual position of the captured brick wall images within the entire building. Consequently, it is challenging to map the results from the crack detection onto the real-scene 3D model. In this context, close-range photogrammetry technology can address the aforementioned problems [7-8] as it allows for continuous close-range shooting of the brick wall structure at a distance of 40cm or 50cm, controlling the image overlap rate to over 60%, and thereby determining the position of the captured images within the overall building imagery. Sun [9] successfully integrated close-range photography and oblique photography to construct a real-scene 3D model applied to the detection of apparent cracks in arch bridges. In general, in arch bridges made of concrete it is easier to detect apparent cracks using target detection algorithm of image. In contrast, in architectural heritage, which includes wooden structures and brick-concrete structures, the detection of apparent cracks empowered by real-scene 3D is more challenging compared to arch bridges.

To promote research on the detection of apparent cracks in architectural heritage empowered by real-scene 3D, this paper takes the typical wind-rain bridges situated along the Xiao-He Ancient Road as the research object. The wind-rain bridges in the Xiao-He Ancient Road area have horse-head walls or brick pavilions at both ends, while the middle corridor-bridge section primarily features a timber structure. These wind-rain bridges were constructed in the period from the Southern Song Dynasty to the late Qing Dynasty and over time cracks have appeared in both the brick-concrete structures and timber structures of these wind-rain bridges. Therefore, conducting research on the detection of apparent cracks in the wind-rain bridge architectural heritage along the Xiao-He Ancient Road empowered by real-scene 3D has practical significance and can promote the application of real-scene 3D in cultural relic surveys.

2. Introduction to technical principles and analysis of technical difficulties

2.1. Technical principles of real-scene 3D empowered detection of apparent building cracks

The core principle of real-scene 3D empowered detection of apparent building cracks is based on acquiring continuous high-definition image data of building surfaces using close-range photogrammetry and oblique photogrammetry technologies. Deep learning algorithms are then used to train and identify cracks within these images, completing the automatic annotation of apparent building cracks. This facilitates the analysis of factors that have caused the cracks and the assessment of the service performance of building components. Relying on real-scene 3D modeling software (such as Context

Capture), the collected building images are used for 3D reconstruction. The generated real-scene 3D model is imported into the Unity3D platform [10-11] to achieve precise positioning and visual display of the crack identification results within the 3D scene. Finally, comprehensive presentation of crack information and its cause analysis is achieved within the Unity3D software.

2.2. Difficulties in real-scene 3D data acquisition and modeling

Close-range photogrammetry and oblique photogrammetry technologies are primarily used for building exterior image acquisition and real-scene 3D model reconstruction. However, within the interior spaces of buildings, due to complex structures and severe obstructions, it is difficult to directly conduct close-range photogrammetry. Therefore, systematically collecting images of the interior spaces of the wind-rain bridge buildings to achieve integrated real-scene 3D modeling of both the interior and exterior has become one of the difficulties in real-scene 3D data acquisition and modeling for the wind-rain bridge buildings along the Xiao-He Ancient Road.

For the Xiao-He Ancient Road wind-rain bridges, the close-range photogrammetry work was divided, according to structural type, into brick-concrete structure horse-head wall sections and timber structure bridge corridor sections, implementing classified storage to facilitate subsequent crack identification based on material differences. For the horse-head wall sections, where there is no external obstruction, images were primarily captured using a drone equipped with a five-lens camera. The flight altitude was controlled at the one-third division line of the building's height, and the distance between the drone and the wall surface maintained at approximately 0.5 meters to ensure clear surface textures and patterns were obtained. For the interior areas of the wind-rain bridge, the drone's flight path needed to be planned in advance to navigate through the limited space. For areas within the building interior where the drone's flight was obstructed, handheld high-definition cameras were used for manual supplementary photography of the building's interior spaces. This was complemented by image data acquisition using the five-lens camera, thereby completing the close-range photogrammetry of the wind-rain bridge's interior spaces. For the bridge corridor timber structure within the interior, a combination of roof-center-axis orbiting flight and internal traversing flight was adopted to achieve comprehensive image collection. Manual supplementary photography was also used to complete data acquisition in high-risk areas encountered during flight. During the data acquisition process, a total of 1,119 images were obtained. Specifically, 354 images were captured for the horse-head wall sections, taking 10 minutes. For the timber structure sections inside the wind-rain bridge, 765 images were captured, taking 15 minutes. The overlap rate for all images was strictly controlled to be over 60%.

2.3. Crack image recognition technology for wind-rain bridge building components

The architectural form of the wind-rain bridges along the Xiao-He Ancient Road possesses distinct characteristics: the main bridge corridor structure is timber, while the ends feature brick-concrete structures, namely horse-head walls or pavilions. This characteristic distinguishes them from wind-rain bridges in other southern regions, such as Dong ethnic wind-rain bridges and wooden arch corridor bridges in Fujian and Zhejiang, which are primarily pure timber structures without brick-concrete components.

The presence of both timber structural components and brick-concrete structural components in the wind-rain bridges of the Xiao-He Ancient Road region poses significant challenges for the automatic identification of cracks in building images using deep learning. This is specifically manifested as follows: if a unified YOLO [12-13] series object detection algorithm is used for identifying cracks in wind-rain bridge images, while it can achieve the annotation of crack locations, it cannot accurately obtain quantitative information about cracks in brick-concrete structures, such as crack width and length. Conversely, if semantic segmentation models (like U-Net [14] or DeepLabV3+ [15]) are used, they can achieve fine annotation of brick-concrete cracks. However, when applied to timber structures, not only does the annotation cost increase significantly, but identification accuracy is also less than ideal. Therefore, the architectural forms and material characteristics of the wind-rain bridges along the Xiao-He Ancient Road, to some extent, limit the research and development of real-scene 3D empowered technologies for detecting apparent cracks in their structures. Consequently, this paper adopts a categorized processing strategy: for the brick-concrete horse-head wall sections, semantic segmentation models like DeepLabV3+ were used to achieve precise extraction of quantitative indicators such as crack shape, width, and length, thereby supporting the quantitative assessment of structural damage. For the timber bridge corridor sections, object detection models like YOLO were employed to achieve fast and robust localization of cracks in the wind-rain bridge structure.

In summary, to utilize deep learning algorithms for crack identification in wind-rain bridge buildings, it is necessary to classify and store images according to the type of building components. Then, appropriate deep learning algorithms are selected respectively for the identification and annotation of cracks in these building components. The close-range photogrammetry data containing the marked cracks is then used to create a real-scene 3D model with Context Capture software. Finally, relying on the Unity3D software, the architectural style of the wind-rain bridge, the causes of crack formation, and repair solutions are displayed. This approach enables efficient and accurate detection and presentation of cracks in wind-rain bridge buildings.

3. Engineering practice and application

3.1. *The wind-rain bridge group of the Fuchuan Yao Ethnicity*

The Wind-Rain Bridge group of the Fuchuan Yao ethnicity, designated as a National Key Cultural Relics Protection Unit, constitutes a significant cultural heritage site along the Xiao-He Ancient Road. Stretching from Yongzhou, Hunan Province to Hezhou, Guangxi Zhuang Autonomous Region, the Xiao-He Ancient Road hosts the Fuchuan Yao Wind-Rain Bridge group, which is the largest and best-preserved collection, comprising 27 bridges in total. Their construction (or reconstruction) periods span approximately 300 years, from the 30th year of the Wanli era of the Ming Dynasty (1602) to the 30th year of the Guangxu era of the Qing Dynasty (1904), consequently, this bridge group possesses outstanding cultural value. Structurally, moreover, they integrate brick, stone, and timber construction, featuring horse-head walls (or pavilions) at both ends and a timber-structured bridge corridor in the middle, which distinguishes their architectural form from wind-rain bridges in other regions. Their cultural heritage value is primarily reflected in various aspects, including architectural components, component construction techniques, murals, wooden carvings, brick carvings, and inscribed stelae. The area in which the Fuchuan Wind-Rain Bridges along the Xiao-He Ancient Road are located is shown in Figure 1.

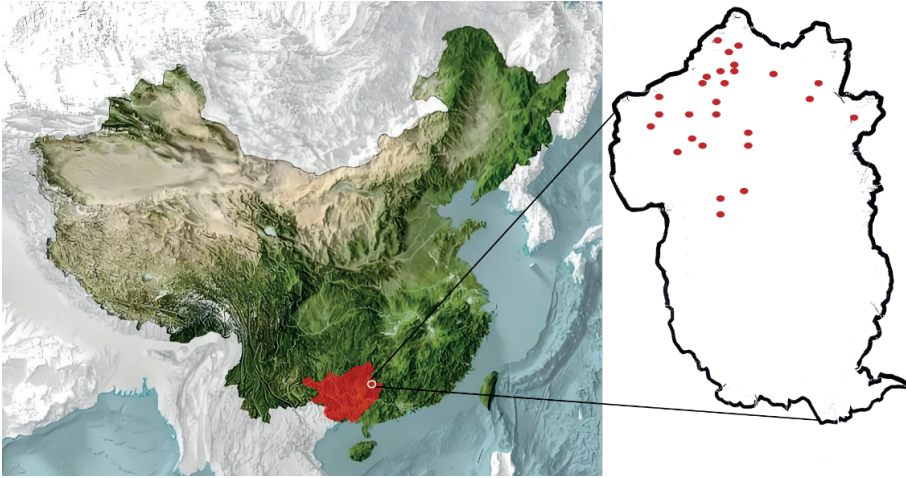


Figure 1. Distribution area of wind-rain bridges in the Fuchuan Region.

The Huilan Wind-Rain Bridge, a typical representative of the wind-rain bridge group along the Xiao-He Ancient Road, is located in Chaodong Town, Fuchuan County, Hezhou City, Guangxi. It spans the Huangsha River, connecting Youmu Village and Mulong Village. Constructed in 1602, the bridge features a corridor and pavilion with a depth of ten bays, a column-and-tie timber frame, and small blue-tile roofing. The entire structure is composed of a three-arch stone bridge, a bridge corridor, bridge pavilions, multi-story pavilions, and horse-head walls (Figure 2). The brick walls of the multi-story pavilions are decorated with multiple murals depicting figures, flowers, and birds. The four upturned eaves at the roof corners soar elegantly, and the ridge ornaments feature exquisitely crafted clay sculptures. The bridge largely retains its original appearance, possessing significant cultural value.



Figure 2. Aerial view of the Huilan wind-rain bridge

The prolonged service life of the wind-rain bridge structures coupled with the cumulative effects of geological environmental changes, natural disasters, such as heavy rainfall and floods, and human-induced damage, has meant that the Fuchuan wind-rain bridge group has sustained varying degrees of damage. This includes the non-uniform settlement of the stone arch bridges, displacement of the horse-head walls, and weathering cracks in both the brick walls and wooden components. Therefore, it is necessary to conduct a comprehensive survey and statistical analysis of the current deterioration status of the wind-rain bridge structures. This entails constructing high-precision real-scene 3D models and integrating crack information and cause analysis within these models. The specific technical pathway is as follows: acquire building images through close-range photogrammetry; identify and mark cracks based on deep learning algorithms (using the DeeplabV3+ algorithm for brick wall crack identification and the YOLO_V5 algorithm for wooden component crack identification); map the identification results onto the real-scene 3D model for visual feedback; and present the research findings utilizing Unity3D software. The detailed technical workflow is shown in Figure 3. This method can effectively promote the in-depth application of real-scene 3D models in cultural heritage surveys and digital preservation.

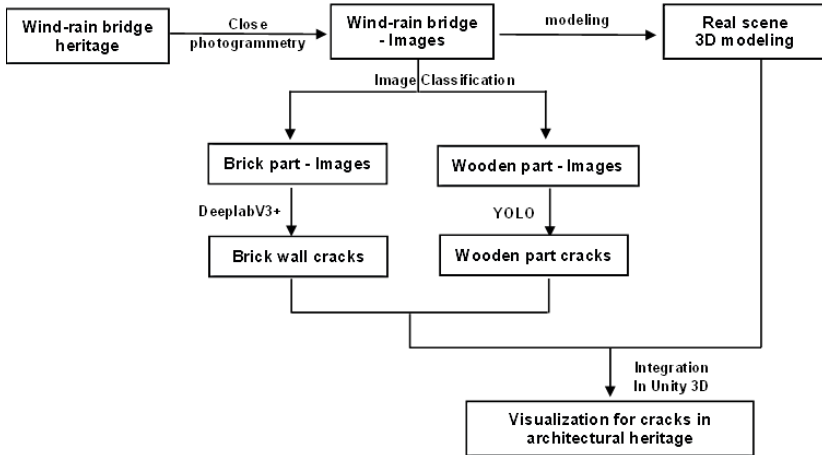


Figure 3. Technical pathway for apparent crack detection in wind-rain bridges.

3.2. Detecting cracks in brick-concrete structure images

During the data acquisition process of close-range photogrammetry for real-scene 3D modeling, it is necessary to extensively collect building images at close range using high-definition cameras. These building images are categorized into brick wall structure images and timber structure images. However, the wind-rain bridge group in the Fuchuan region possesses a vast amount of brick wall structure image data. Manually annotating crack patterns one by one requires substantial human effort and time in terms of cost. Therefore, utilizing deep learning algorithms for automated identification methods can effectively reduce the cost of crack identification and annotation. For the purpose of model training, typical crack images from the brick wall structure were selected. Relevant research results indicate that the DeepLabv3+ algorithm in deep learning demonstrates stronger accuracy compared to other algorithms, enabling effective identification of cracks and their shapes in brick walls.

The brick wall structures of the horse-head wall buildings in the Xiao-He Ancient Road area feature colors that integrate Han and Yao ethnic characteristics. Specifically, brick walls with Yao characteristics primarily use red as the main tone, those with Han characteristics are predominantly gray-white, and those blending Han and Yao features mix red and grayish white. This characteristic increases the difficulty of identifying cracks in the horse-head wall structures of the wind-rain bridges. Consequently, it is necessary to establish a dedicated brick wall crack dataset. A brick wall crack dataset for the Xiao-He Ancient Road area was obtained through close-range photogrammetry. The images collected via close-range photogrammetry were cut into sub-image sets of brick wall cracks with a resolution of 512×512. The image data annotation tool Labelme was then used to annotate along the contours of the brick wall cracks.

The wind-rain bridges along the Xiao-He Ancient Road have a history of several hundred years. The cracks in their horse-head wall brick masonry structures are already mature, and the crack widths are relatively noticeable. Immature cracks only exist on the surface of the brick walls without penetrating through and have minimal impact on the structural stability of the brick walls. Therefore, this study marks the outer contours of the brick wall cracks in the building images and employs a method of widening the annotated cracks in the brick wall images. The DeepLabv3+ deep learning algorithm was used to train the brick wall structure image dataset from the Xiao-He Ancient Road area. Comparing the training results with the manually annotated data showed that the accuracy of DeepLabv3+ in identifying brick wall cracks reached 96%. The trained DeepLabv3+ algorithm was then used to identify cracks in the horse-head wall structures of the wind-rain bridges in the Xiao-He Ancient Road area (as shown in Figure 4). The results of the identification are shown in Figure 5. To highlight the crack identification results, the brick wall images are set to black, and the cracks are set to white.



Figure 4. Images of the cracks in the horse-head wall of the wind-rain bridge. (A) Crack area 1; (B) crack area 2; (C) crack area 3.

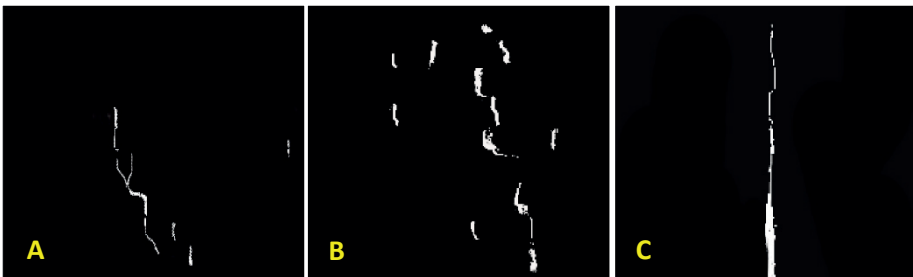


Figure 5. Results of crack identification for the horse-head wall of the wind-rain bridge. (A) Crack identification area 1; (B) crack identification area 2; (C) crack identification area 3.

From the identification results in Figure 5, it can be seen that crack area (A) shows cracks appearing in the mortar portion of a local area of the horse-head wall, with the crack development direction forming an angle of approximately 70° with the horizontal line. The primary cause of these cracks is the non-uniform settlement of the brick wall near the horse-head wall arch. Crack area (B) in the brick wall mainly exhibits localized crushing, primarily because the wooden beam of the corridor bridge directly acts on the brick wall, and the force exceeds the bearing capacity of the brick wall, causing local crushing. Crack area (C) in the brick wall shows vertical penetration cracks. This is mainly due to the fact that the bottom of the brick wall is supported by stone strips, and inconsistent settlement between these stone strips has led to vertical cracks in the upper brick wall.

3.3. Crack identification in timber structure images

Due to the complex forms of the connections of the structural timber components in wind-rain bridge buildings, it is difficult to capture images close-up and directly facing the areas of the timber structures. The effectiveness of using semantic segmentation model algorithms is not significant, as they cannot precisely determine the shape and dimensions of cracks in timber structures. Furthermore, since structural timber components possess certain capacities to resist tension, compression, bending, and torsion, cracks formed in local areas of the timber structure are generally insufficient to affect the overall safety, stability, and service performance of the wind-rain bridge. Considering the above reasons, the YOLO_V5 object detection algorithm was adopted to rapidly identify the location of the cracks in the timber structure of the wind-rain bridge, and bounding boxes were used to mark the position of the cracks.

As the interior areas of the wind-rain bridge buildings along the Xiao-He Ancient Road are connected to the exterior facades, close-range photogrammetry techniques can be used to construct a real-scene 3D model of the wind-rain bridge. This model allows for the observation of the interior spaces of the wind-rain bridge structure. A drone equipped with a high-definition camera was used to fly through the interior areas and capture image data of the structural timber components. Cracks visible in the timber structure images are primarily located at the tops of columns, the ends of beams, and areas such as the architraves. Since identifying cracks in the timber structure only requires box-selection annotation of the cracks, the collected images were labeled. The Label-Img tool was used to generate txt files containing the annotation data. These files include the coordinates of the bounding boxes that mark the cracks in the collected timber structure images. The annotated dataset of timber structure images serves as training samples for a YOLO_V5 model to perform crack detection.

The performance of the trained YOLO_V5 model was evaluated on a separate test set. It achieved a precision of 92.5%, a recall of 88.1%, and a mean Average Precision of 89.4%, demonstrating capability in locating cracks in the timber structures. After completing the training on the images of the cracks in the timber structures from the Xiao-He Ancient Road area, the images obtained via close-range photogrammetry of the wind-rain bridge (Figure 6) were used for testing. The structural timber components are free from surface coatings, such as paint or plaster, thus minimizing potential interference with the YOLO_V5 algorithm's ability to detect cracks in the timber structure. The test results applying the YOLO_V5 algorithm to the timber structure are shown in Figure 7.

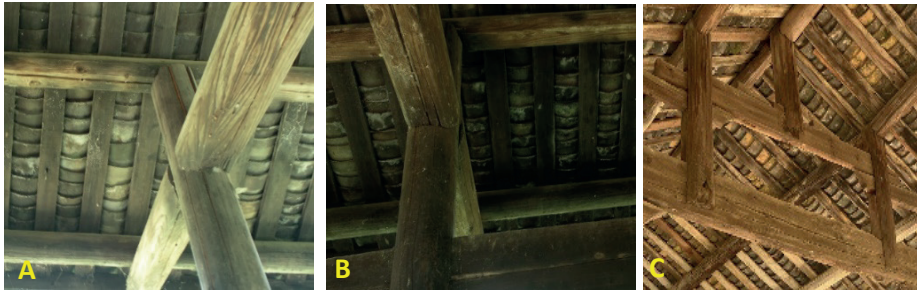


Figure 6. Images of cracks in the timber structure of the wind-rain bridge. (A) Crack zone 1; (B) crack zone 2; (C) crack zone 3.

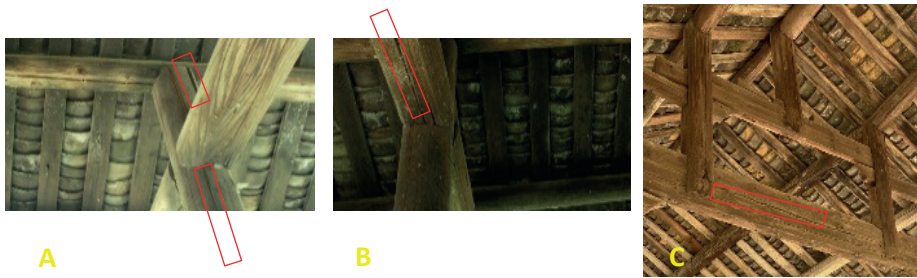


Figure 7. Images of cracks in the timber structure of the wind-rain bridge. (A) Crack identification 1; (B) crack identification 2; (C) crack identification 3.

Based on the results obtained using YOLO_V5 to identify the cracks in the timber structure, it can be concluded that the cracks in the timber structures of the wind-rain bridges along the Xiao-He Ancient Road primarily develop longitudinally along the timber members and are mainly found at the mortise-tenon connections between components. The main reasons for the formation of these cracks are that the machining process at the mortise-tenon joints damages the continuity and integrity of the timber member in the longitudinal direction. Additionally, the mortise-tenon connection points are subjected to the highest stresses relative to the entire member.

3.4. Visualization of apparent cracks in the wind-rain bridge within the real-scene 3D model

By integrating the image data collected through close-range photogrammetry using relevant software, a real-scene 3D model of the wind-rain bridge structure along the Xiao-He Ancient Road was constructed. The high overlap rate (over 60%) of the close-range images ensured the geometric accuracy of the model and provided a reliable foundation for mapping the 2D crack identification results back into the 3D space. The estimated spatial localization error of the cracks in the 3D model is within ± 5 cm, which is sufficient for practical conservation surveys and damage assessment. This completed real-scene 3D model of the wind-rain bridge was then imported into the Unity3D software to serve as the base model for the real-scene 3D model showcasing apparent cracks in the Xiao-He Ancient Road wind-rain bridge structure.

After importing the real-scene 3D model into Unity3D, the collected images of the wind-rain bridge structure were categorized into two main types: timber structure and brick-concrete structure. The trained DeepLabV3+ and YOLO algorithms from this study were then used respectively to identify cracks in the timber structure and brick-concrete structure images. The identified crack images were simultaneously located and imported into the Unity3D software and mapped onto the surface of the real-scene 3D model. Trigger points for locating the cracks in the images were set within Unity3D, forming a visualization platform for detecting apparent cracks in the Xiao-He Ancient Road wind-rain bridge structure, as detailed in Figure 8.



Figure 8. Visualization platform for apparent crack detection of the wind-rain bridge.

In Figure 8, the blue markers locate cracks in the brick-concrete structure, while the orange markers locate cracks in the timber structure. Dialog boxes are set at these marker points. The content of these dialog boxes describes the crack's shape, dimensions, and location, and allows for downloading images of the crack identification results. This serves as a digital archive of the apparent crack detection results for the wind-rain bridges along the Xiao-He Ancient Road. Hovering the mouse over a marker point, an information window pops up displaying details about the crack form. Clicking on a marker point directly switches the perspective to the crack location at that point, enabling intuitive observation of the relationship between the crack and the surrounding structure. Within the Unity3D software, users can freely navigate the real-scene 3D model to view the crack patterns. Staff from cultural relic protection units can intuitively observe the real-scene 3D model of the Xiao-He Ancient Road wind-rain bridge and its apparent crack characteristics, allowing them to accurately assess the service performance of the bridge.

4. Conclusions

Utilizing close-range photogrammetry, this study developed a high-precision real-scene 3D model of the wind-rain bridges along the Xiao-He Ancient Road. By integrating DeepLabV3+ and YOLO deep learning algorithms, we successfully achieved

accurate extraction of crack morphology in the brick walls and precise localization of cracks in the timber structures. The incorporation of these results into a 3D visualization platform allows for intuitive display of both the heritage structure and its associated damage, enabling visual documentation of apparent cracks in architectural heritage facilitated by real-scene 3D technology.

The proposed method serves as a semi-automated pipeline for crack detection and visualization. While the deep learning algorithms substantially automate the identification process, certain stages still require manual intervention including initial image sorting by structural type and the configuration of trigger points in Unity3D. Despite this, the overall improvement in efficiency is considerable. For instance, manual annotation of a single brick wall image for semantic segmentation typically takes 3–5 minutes, whereas the trained DeepLabV3+ model processes images at a rate of approximately 10 per second. Similarly, the YOLO_V5 model automates the labor-intensive task of detecting cracks in timber components.

Beyond its initial validation on the wind-rain bridges of the Xiao-He Ancient Road, the core technical framework of this method demonstrates significant potential for mixed-material structures, such as temples, ancient pagodas, and traditional dwellings. The study provides a reliable technical pathway for monitoring architectural heritage.

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Summary

To foster the in-depth application of real-scene 3D technology in architectural heritage conservation, this study focuses on the wind-rain bridges along the Xiao-He Ancient Road (China) and conducts research on a visualization method for apparent cracks based on real-scene 3D modeling. High-resolution images of the bridges were obtained through close-range photogrammetry, enabling the construction of a detailed real-scene 3D model. Using established algorithms such as DeepLabV3+ and YOLO, cracks in the architectural images of the wind-rain bridges were identified. Leveraging the multi-view overlap of the close-range images, the crack detection results from the deep learning algorithms were accurately located within the real-scene 3D model of the bridges. On this basis, the real-scene 3D model and the crack identification results were integrated into the Unity3D platform, achieving visualization of apparent cracks in the wind-rain bridge. The proposed method is directly applicable to heritage surveys, providing technical support for compiling digital archives of apparent cracks. These archives are of significant value as they can directly inform future conservation planning and monitoring strategies.

Riassunto

Al fine di promuovere l'applicazione approfondita della tecnologia tridimensionale in contesti reali per la conservazione del patrimonio architettonico, lo studio in esame si focalizza sui ponti antivento e antipioggia situati lungo l'antica strada Xiao-He, in Cina. Esso conduce una ricerca su un metodo di visualizzazione delle crepe apparenti basato sulla modellazione tridimensionale in ambienti reali. Le immagini ad alta risoluzione dei ponti sono state ottenute mediante l'impiego della fotogrammetria a distanza ravvicinata, permettendo così la realizzazione di un modello tridimensionale dettagliato in contesti reali. L'impiego di algoritmi consolidati quali DeepLabV3+ e YOLO ha consentito l'identificazione delle crepe nelle immagini architettoniche dei ponti antivento e antipioggia. Attraverso l'impiego della sovrapposizione multi-vista delle immagini ravvicinate, i risultati del rilevamento delle crepe ottenuti dagli algoritmi di deep learning sono stati localizzati con precisione all'interno del modello 3D in scena reale dei ponti. In tale ottica, il modello tridimensionale della scena reale e i risultati dell'identificazione delle crepe sono stati integrati nella piattaforma Unity3D, ottenendo la visualizzazione delle crepe apparenti nel ponte resistente al vento e alla pioggia. Il metodo proposto può essere applicato direttamente alle indagini sul patrimonio culturale, fornendo supporto tecnico per la compilazione di archivi digitali delle crepe apparenti. Tali archivi rivestono un valore significativo, in quanto sono in grado di fornire informazioni dirette per la pianificazione futura della conservazione e le strategie di monitoraggio.